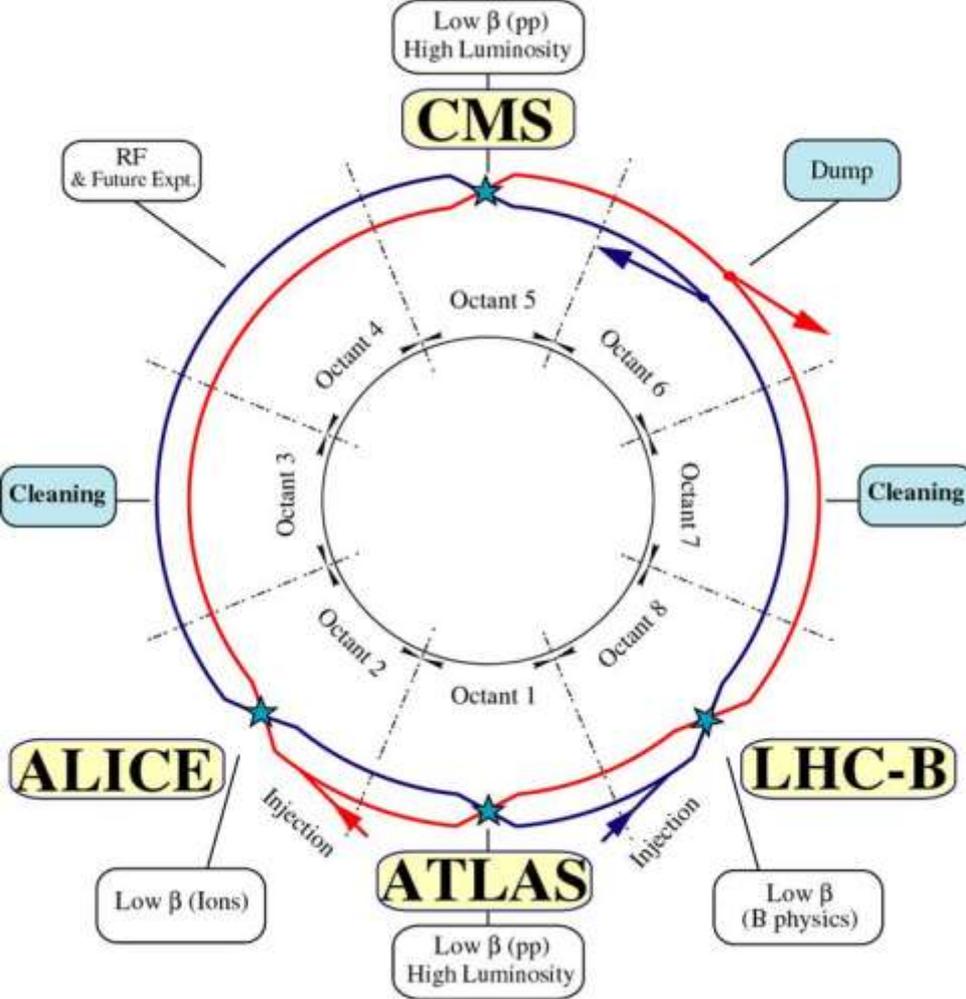
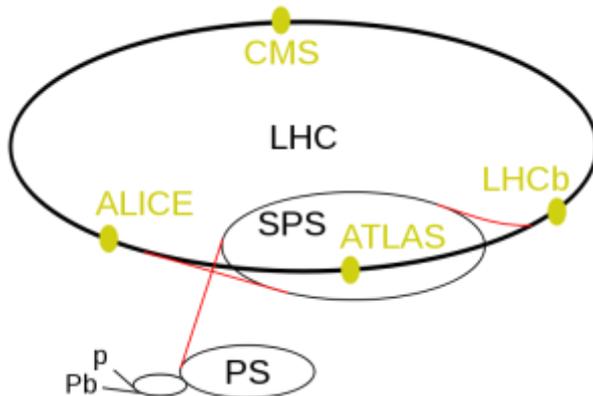


# Новые методы детектирования частиц на LHC



Вторые Черенковские чтения



Л.Н.Смирнова  
НИИЯФ МГУ  
14 апреля 2009г. ФИАН

# Задачи LHC и основные требования к детекторам

LHC предназначен для поиска новых тяжелых частиц – Хиггсовского бозона, суперсимметричных и экзотических частиц в pp-взаимодействиях при энергиях 10-14 ТэВ.

Это означает, что требуется измерять импульсы мюонов, электронов, фотонов и энергии струй до 1 ТэВ.

Задачи эксперимента определяют требования к детекторам:

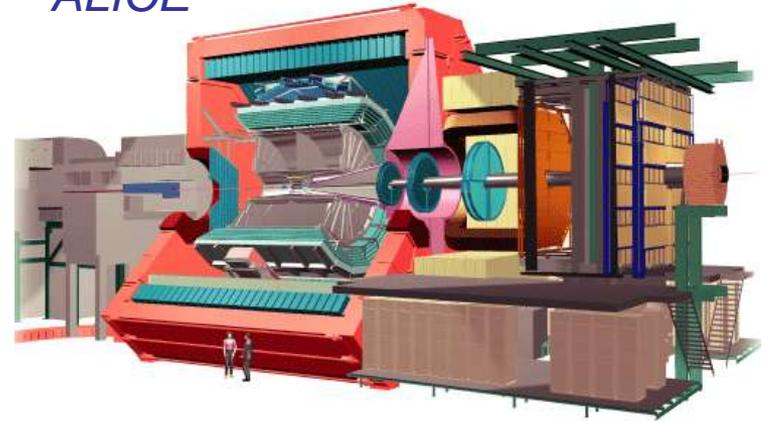
- Высокое разрешение при измерении струй, лептонов, фотонов
- Высокое быстродействие (40МГц)
- Радиационная стойкость детекторов
- Идентификация частиц

# Установки LHC

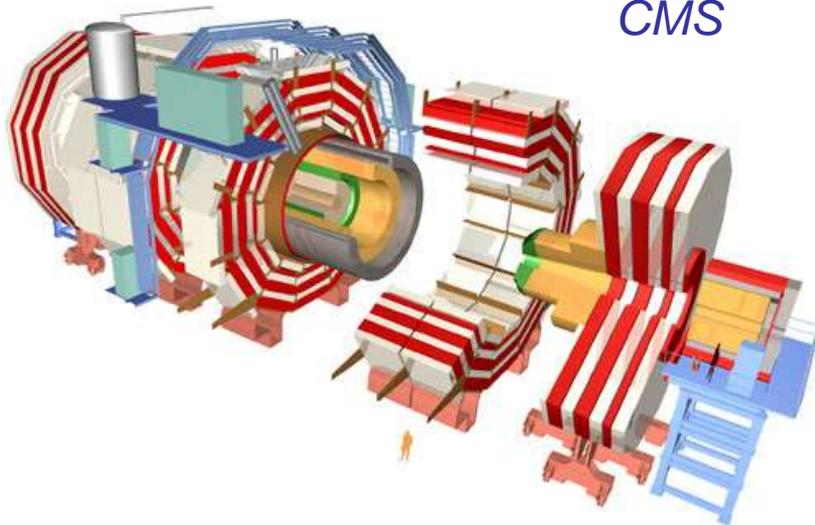
ATLAS



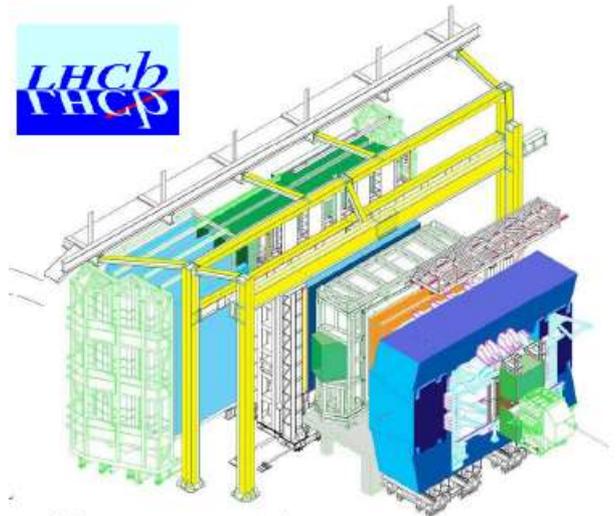
ALICE



CMS

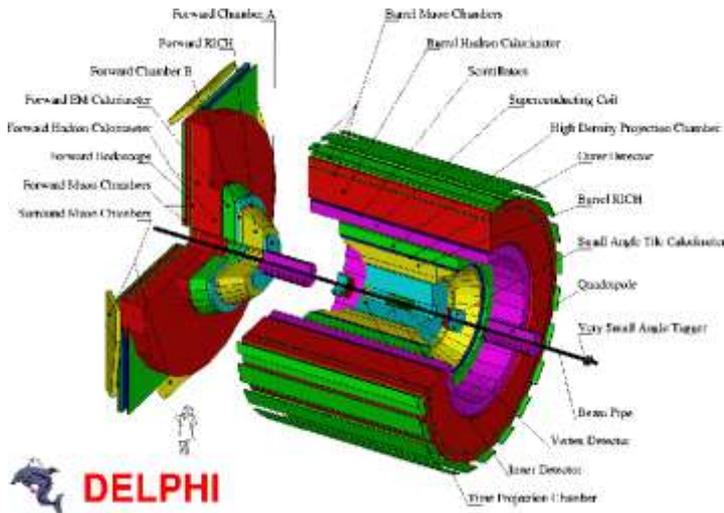


LHC b



# Новое: предельные размеры детекторов и условия работы

*DELPHI: длина 10 м, диаметр 10 м, вес 3 500 т*  
*D0: размеры 15 x 9 x 9 м<sup>3</sup>, вес 5 000 т*



**DELPHI**

*Детекторы LHC:*

*ATLAS*

*CMS*

*общий вес*

*7 000 т*

*12 500 т*

*диаметр*

*25 м*

*15 м*

*длина*

*46 м*

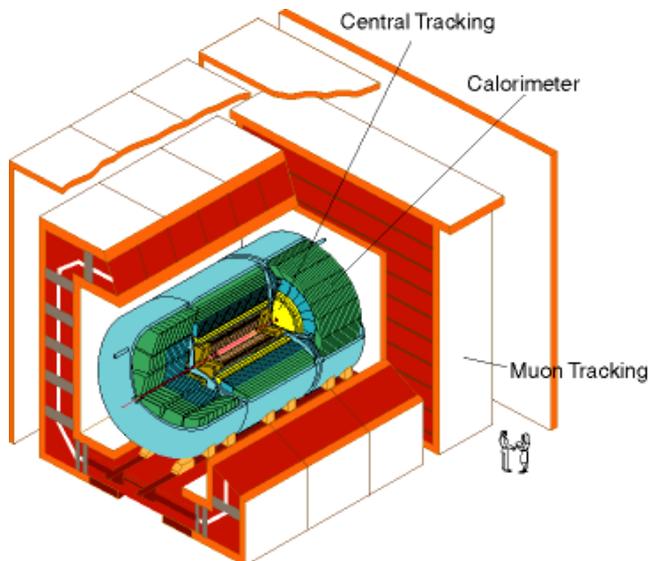
*22 м*

*Поле соленоида*

*2 Т*

*4 Т*

D0



- *Интервал между соударениями 25нс*
- *Наложения событий*
- *Быстрый отбор интересных событий*
- *Высокая гранулярность детекторов*
- *Высокое разрешение измерения импульсов и энергий частиц и струй*
- *Длительный период устойчивой работы в условиях радиационного фона*

# Основные достижения детекторов LHC

- *Магнитные системы ATLAS и CMS*
- *Калориметры*
- *Трековые системы ATLAS и CMS*
- *Мюонный спектрометр ATLAS*
- *Вершинный и RICH детекторы LHCb*
- *TPC детектор ALICE*

# Магнитная система ATLAS

## Toroid system

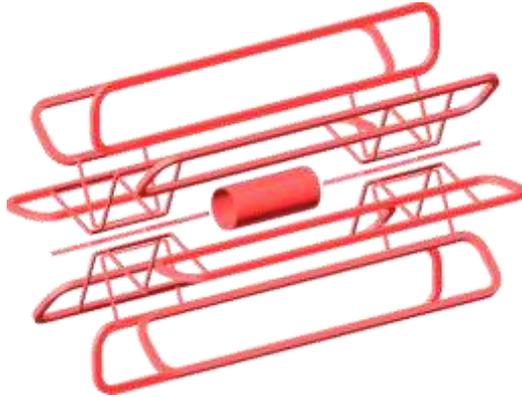


Figure 6. Bare central solenoid in the factory after completion of the coil winding.

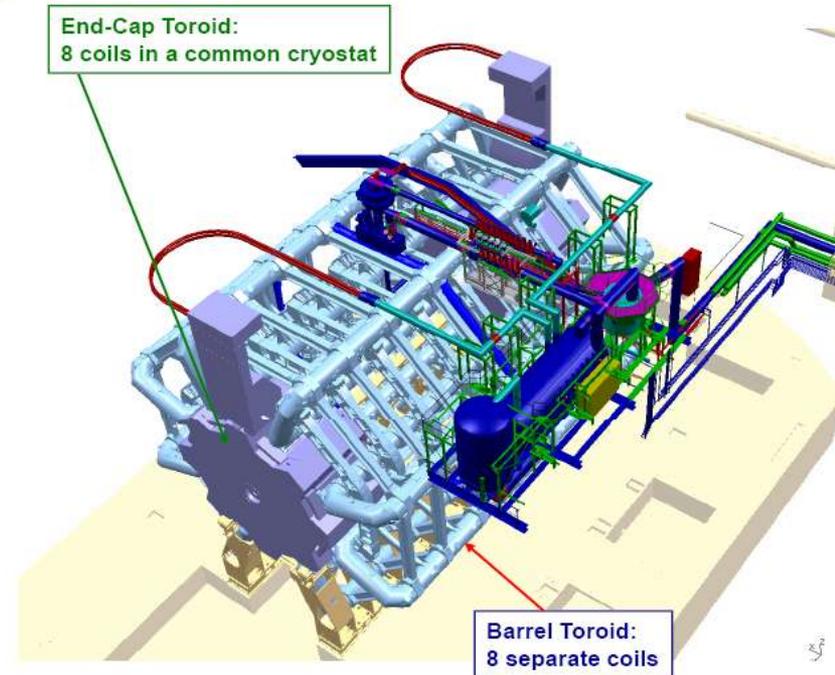
### Barrel Toroid parameters

25.3 m length  
20.1 m outer diameter  
8 coils  
1.08 GJ stored energy  
370 tons cold mass  
830 tons weight  
4 T on superconductor  
56 km Al/NbTi/Cu conductor  
20.5 kA nominal current  
4.7 K working point

### End-Cap Toroid parameters

5.0 m axial length  
10.7 m outer diameter  
2x8 coils  
2x0.25 GJ stored energy  
2x160 tons cold mass  
2x240 tons weight  
4 T on superconductor  
2x13 km Al/NbTi/Cu conductor  
20.5 kA nominal current  
4.7 K working point

EuNPC+DPG, Bochum 2009  
17-Mar-09, P.Jenni (CERN)



LHC

52

Состоит из центрального тороида, двух торцевых и соленоида

CMS – соленоид 12 м длина, 6 м диаметр

# Сравнительные параметры магнитов

Table 28.10: Progress of superconducting magnets for particle physics detectors.

Experiment	Laboratory	$B$ [T]	Radius [m]	Length [m]	Energy [MJ]	$X/X_0$	$E/M$ [kJ/kg]
TOPAZ*	KEK	1.2	1.45	5.4	20	0.70	4.3
CDF	Tsukuba/Fermi	1.5	1.5	5.07	30	0.84	5.4
VENUS*	KEK	0.75	1.75	5.64	12	0.52	2.8
AMY*	KEK	3	1.29	3	40	‡	
CLEO-II	Cornell	1.5	1.55	3.8	25	2.5	3.7
ALEPH*	Saclay/CERN	1.5	2.75	7.0	130	2.0	5.5
DELPHI*	RAL/CERN	1.2	2.8	7.4	109	1.7	4.2
ZEUS*	INFN/DESY	1.8	1.5	2.85	11	0.9	5.5
H1*	RAL/DESY	1.2	2.8	5.75	120	1.8	4.8
BaBar	INFN/SLAC	1.5	1.5	3.46	27	‡	3.6
D0	Fermi	2.0	0.6	2.73	5.6	0.9	3.7
BELLE	KEK	1.5	1.8	4	42	‡	5.3
BES-III†	IHEP	1.0	1.475	3.5	9.5	‡	2.6
ATLAS-CS†	ATLAS/CERN	2.0	1.25	5.3	38	0.66	7.0
ATLAS-BT†	ATLAS/CERN	1	4.7–9.75	26	1080	(Toroid)	
ATLAS-ET†	ATLAS/CERN	1	0.825–5.35	5	$2 \times 250$	(Toroid)	
CMS†	CMS/CERN	4	6	12.5	2600	‡	12

\* No longer in service

† Detector under construction

‡ EM calorimeter is inside solenoid, so small  $X/X_0$  is not a goal

# Качественные параметры соленоидов ATLAS и CMS:

слева - толщина в радиационных длинах относительно  $B^2R$   
 справа - отношение энергии к величине холодной массы  $E/M$   
 относительно запасенной энергии  $E$

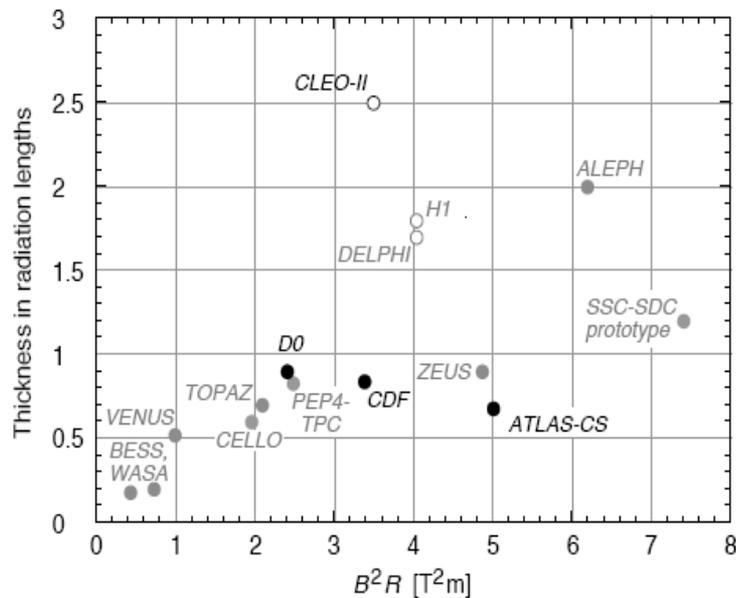


Figure 28.24: Magnet wall thickness in radiation length as a function of  $B^2R$  for various detector solenoids. Gray entries are for magnets not listed in Table 28.10. Open circles are for magnets not designed to be “thin.” The SSC-SDC prototype provided important R&D for LHC magnets.

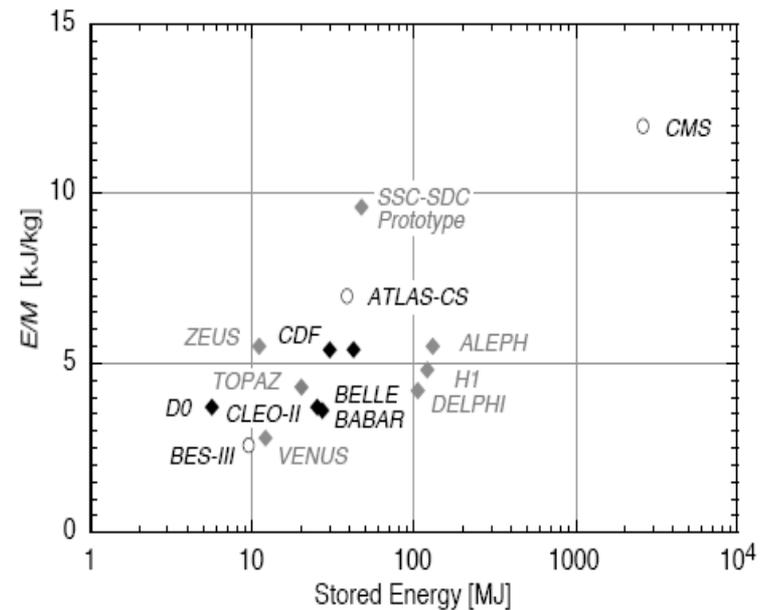
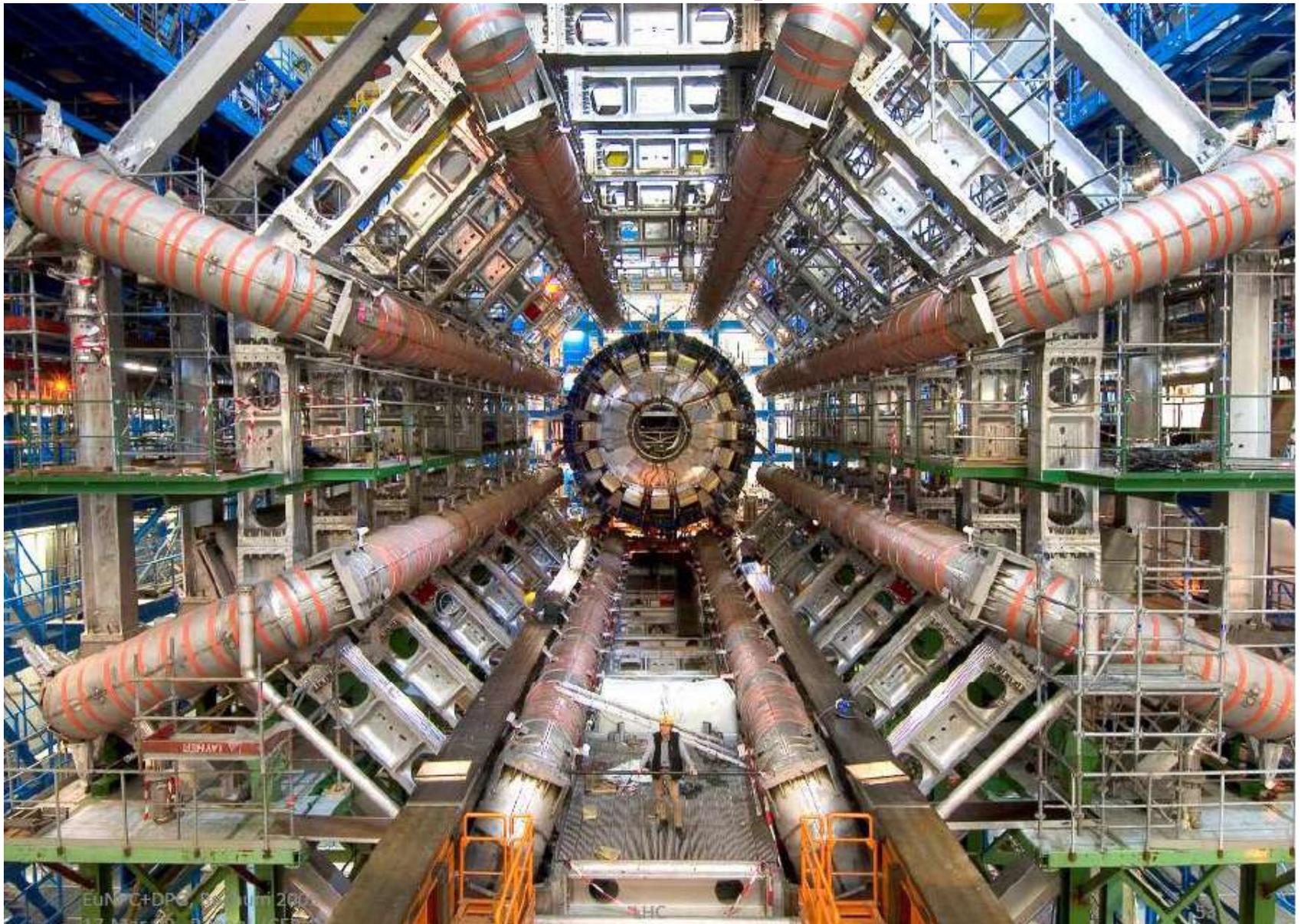


Figure 28.25: Ratio of stored energy to cold mass for thin detector solenoids. Open circles indicate magnets under construction.

# Центральный торонд ATLAS



# Соленоид CMS

## Example of an Engineering Challenge: CMS Solenoid

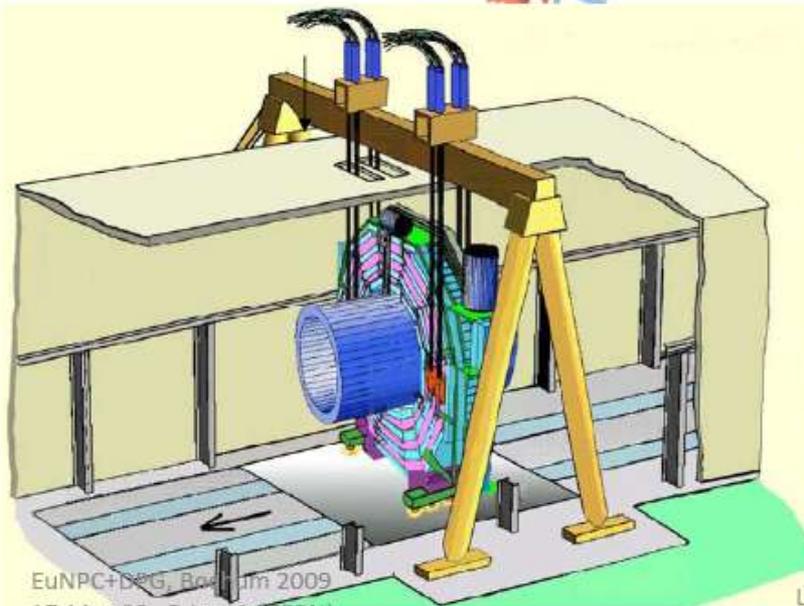
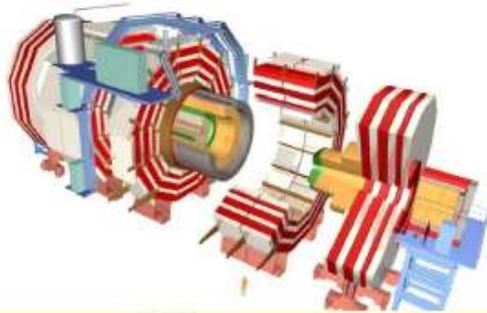


<b><u>CMS solenoid:</u></b>	
Magnetic length	12.5 m
Diameter	6 m
Magnetic field	4 T
Nominal current	20 kA
Stored energy	2.7 GJ
Tested at full current in Summer 2006	



# Соленоид CMS

The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007



EuNPC+DEG, Bordeaux 2009  
17-Mar-09 - P. Jenni (CERN)



In total 15 slices were installed in this way

# Сравнительный анализ систем

- *В обеих установках поле соленоида обеспечивает высокую точность измерений импульсов заряженных частиц вблизи вершины взаимодействия*
- **ATLAS:** *может измерять импульсы мюонов в широком диапазоне углов без использования Внутреннего детектора – но!*  
*Высокая стоимость и большие размеры установки*
- **CMS:** *высокое импульсное разрешение с использованием Внутреннего детектора –*  
*Более компактная установка, ограниченное пространство для калориметров внутри соленоида*



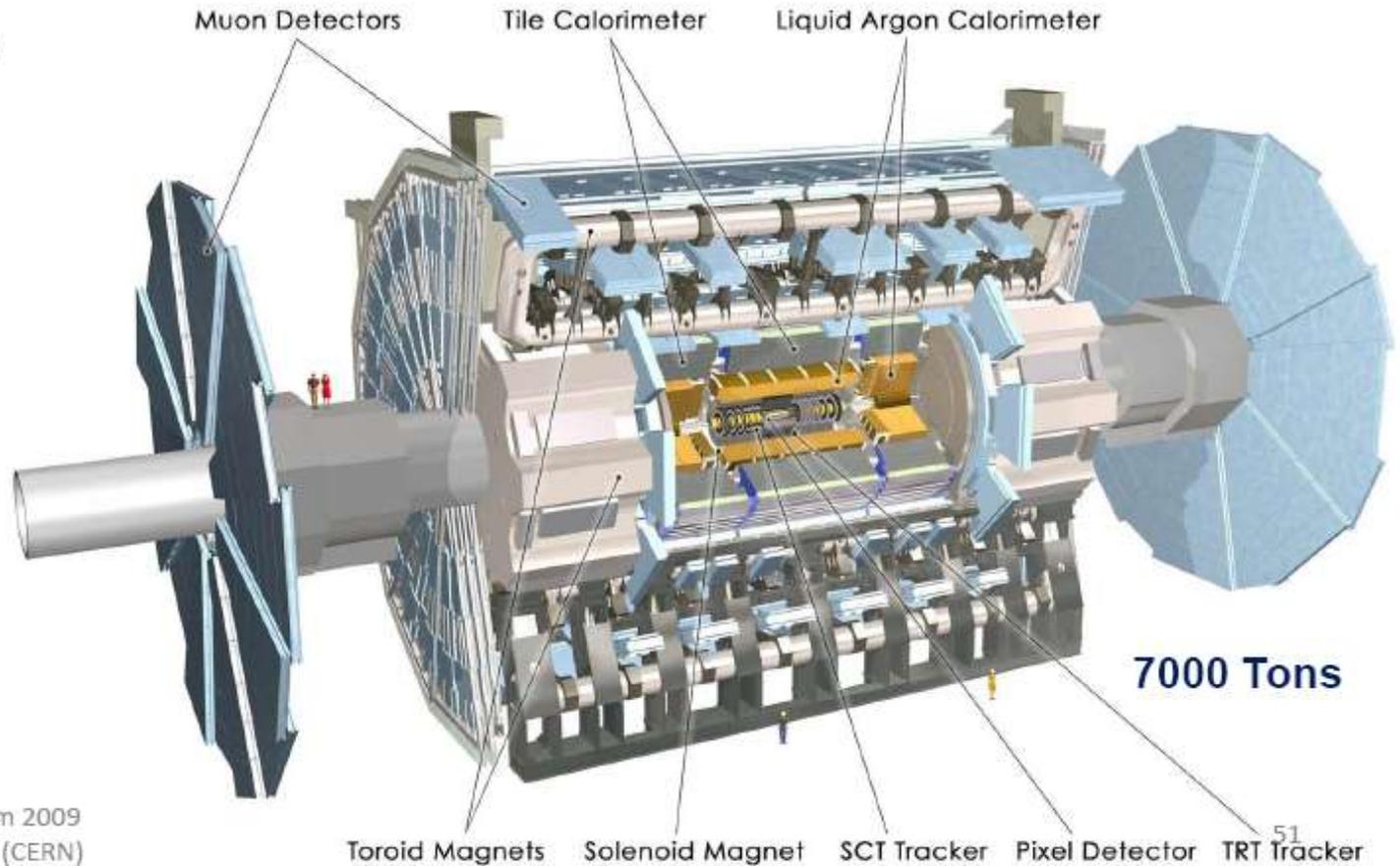
ATLAS superimposed to the 5 floors of building 40

# ATLAS Detector

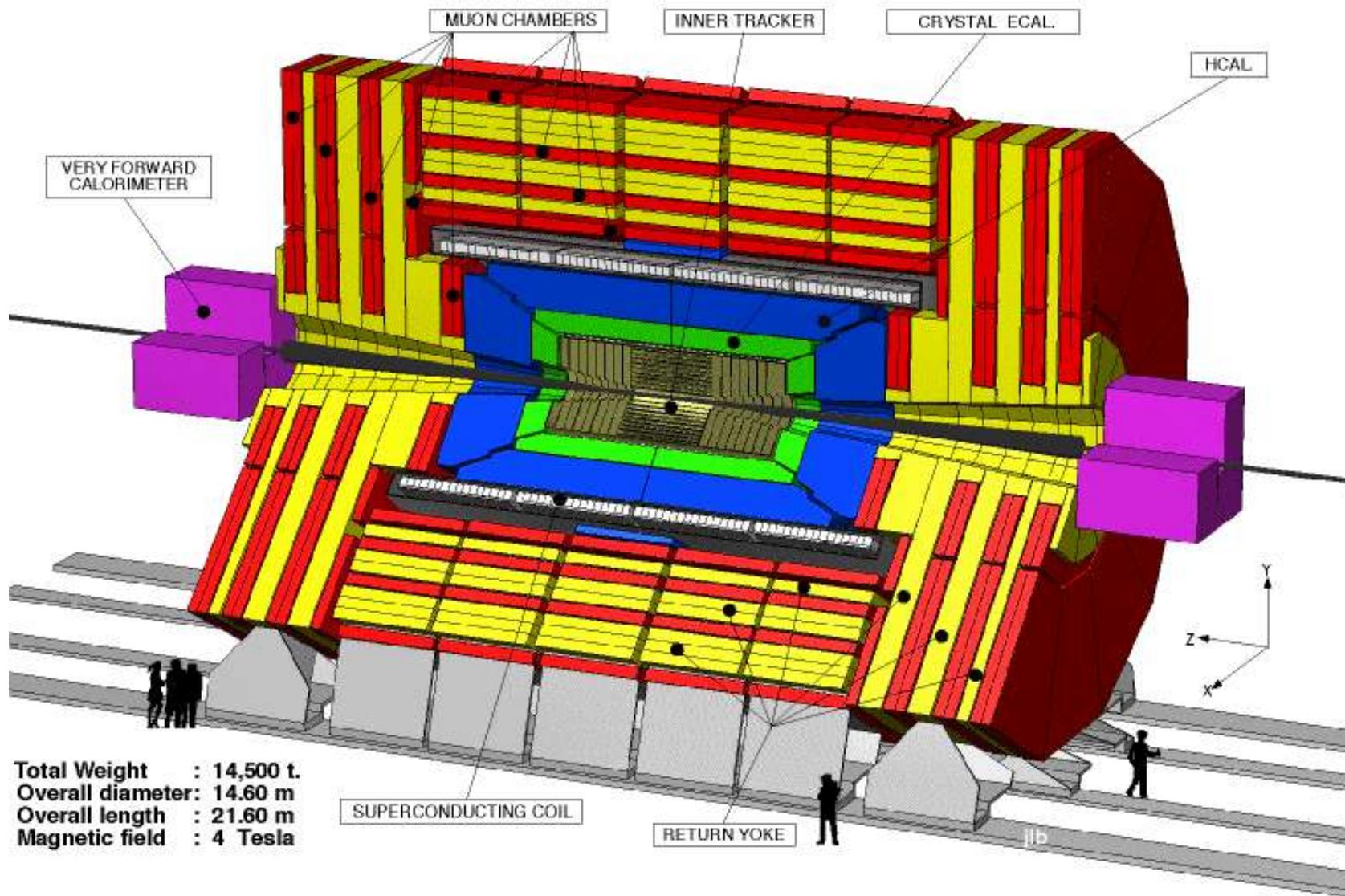
45 m

24 m

7000 Tons

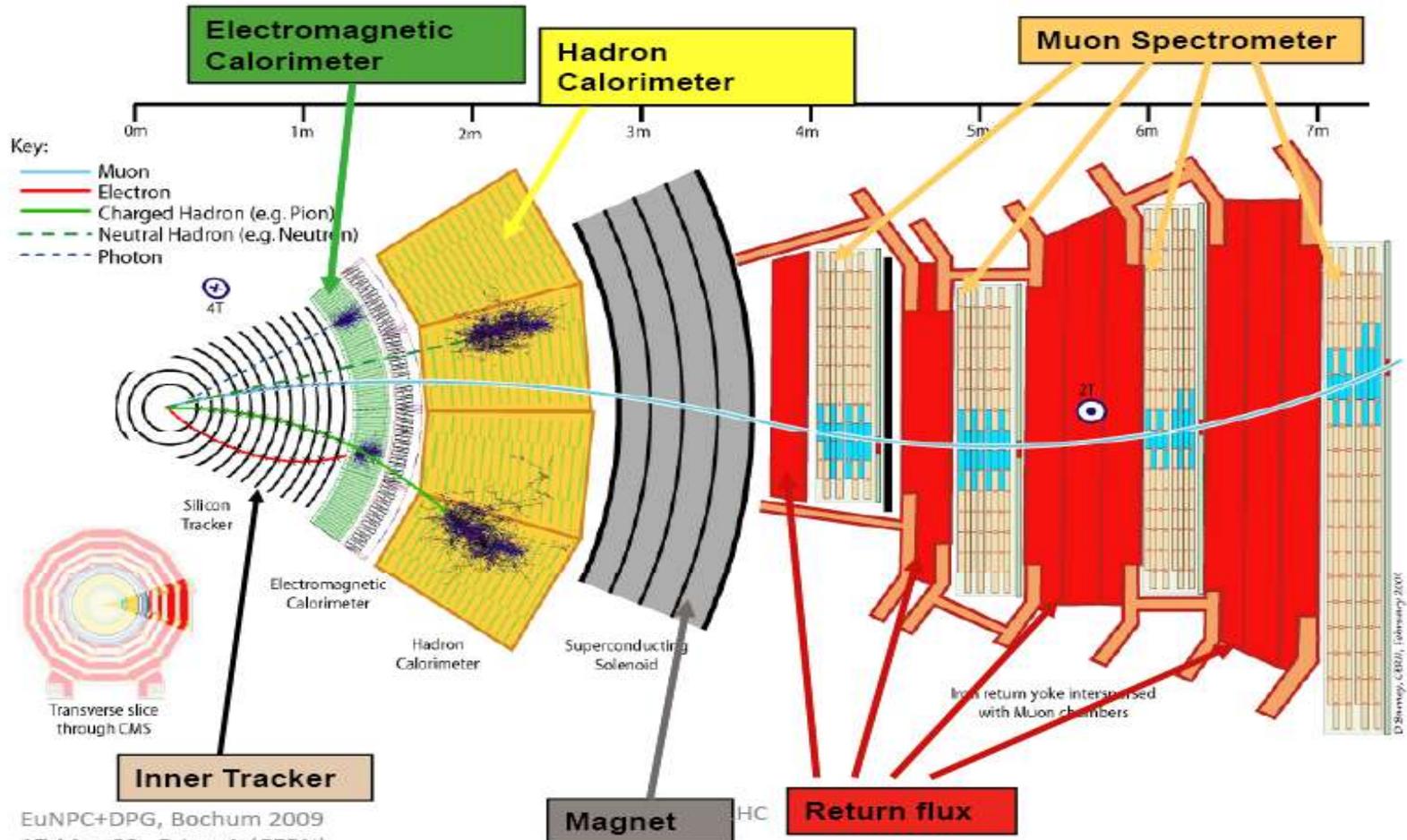


# Установка CMS



# Сектор CMS установки

## A slice through CMS



# Калориметрия ATLAS и CMS

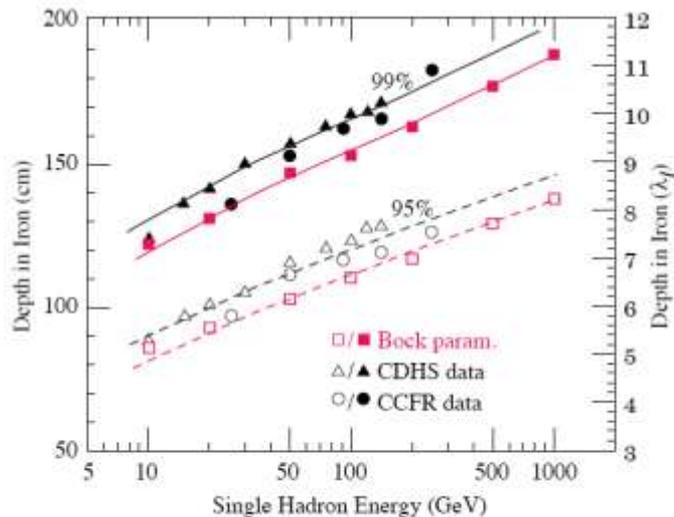


Figure 28.22: Required calorimeter thickness for 95% and 99% hadronic cascade containment in iron, on the basis of data from two large neutrino detectors and Bock's parameterization [143].

- Измерение энергии пиона 1 ТэВ требует 11 длин поглощения  $\lambda$ , или 2 м Fe
- Измерение энергии электрона 1 ТэВ требует до  $30 X_0$ , или 18 см Pb

# Типы калориметров

## Непрерывный –

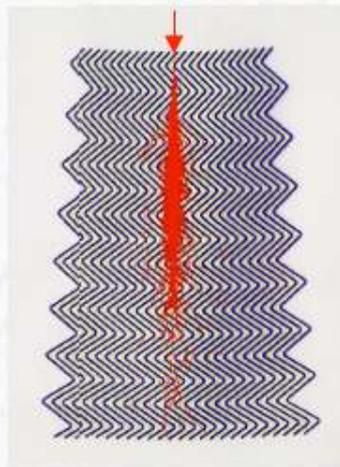
- Каскад развивается внутри вещества с высоким  $X_0$
- Прозрачная среда, высокий световой выход
- Нет потерь частиц
- Низкая гранулярность в продольном направлении

## Составной –

- Тяжелый поглотитель :Fe, Cu, W, Pb, U
- С активным материалом между слоями поглотителя : газовые детекторы, пластиковые сцинтилляторы и сжиженные инертные газы LAr, LKr
- Сегментированное считывание информации



ATLAS LAr  
Calorimeter



# Калориметрия ATLAS и CMS

- Оба адронных калориметра составные, некомпенсированные ( $e/h = 1.4$ )
- Составной *жидкоаргоновый* электромагнитный калориметр **ATLAS** (175 тыс. каналов считывания)
- Непрерывный электромагнитный калориметр **CMS** на кристаллах
- Большой вклад в создание всех калориметров внесли **Россия и ОИЯИ** (Дубна)
- Особое значение имеет разработка и производство кристаллов для электромагнитного калориметра **CMS** ( и **ALICE**), выполненная в России (Богородитск)

**CMS Electron and Photon calorimeter:**  
~ 80 000  $\text{PbWO}_4$  crystals

# Сравнительные параметры кристаллов для ЭМ калориметров (справа) и разрешение ЭМ калориметров (слева)

Parameter:	$\rho$	MP	$X_0^*$	$R_M^*$	$dE/dx$	$\lambda_I^*$
Units:	$\text{g/cm}^3$	$^\circ\text{C}$	cm	cm	MeV/cm	cm
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9
BGO	7.13	1050	1.12	2.23	9.0	22.8
BaF <sub>2</sub>	4.89	1280	2.03	3.10	6.6	30.7
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3
PbWO <sub>4</sub>	8.3	1123	0.89	2.00	10.2	20.7
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9
GSO(Ce)	6.71	1950	1.38	2.23	8.9	22.2

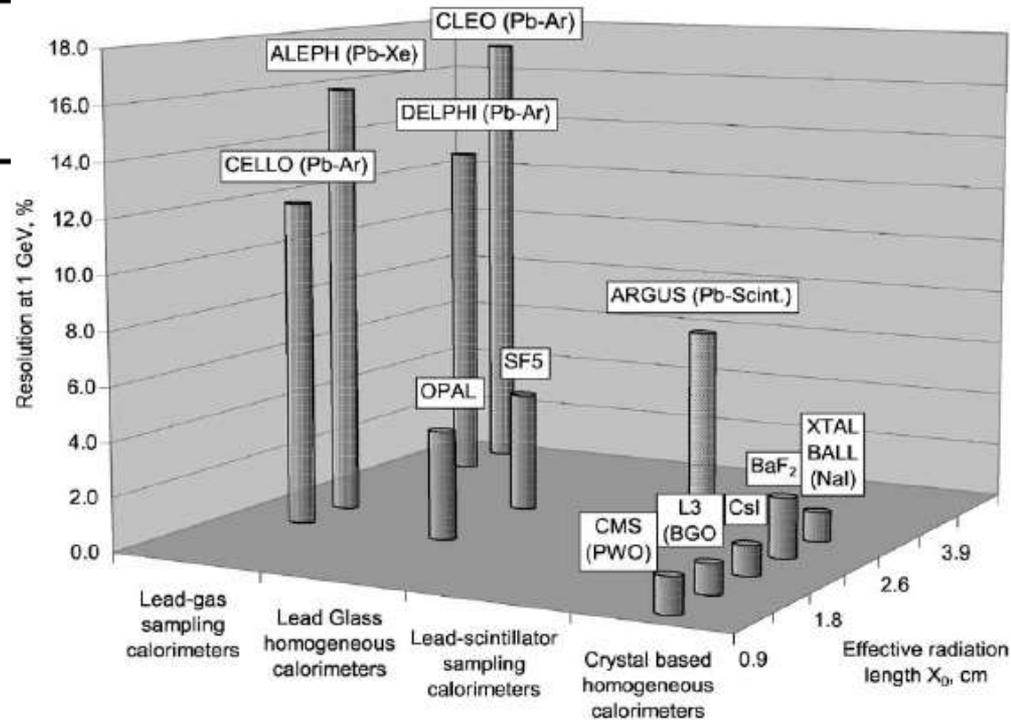


Fig. 1. Energy resolutions of electromagnetic calorimeters in recent years.

# Параметры электромагнитных калориметров

**Table 28.9:** Resolution of typical electromagnetic calorimeters.  $E$  is in GeV.

Technology (Exp.)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub> (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16-18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
PbWO <sub>4</sub> (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20-30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20-30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

# Подготовка кристаллов электромагнитного калориметра CMS

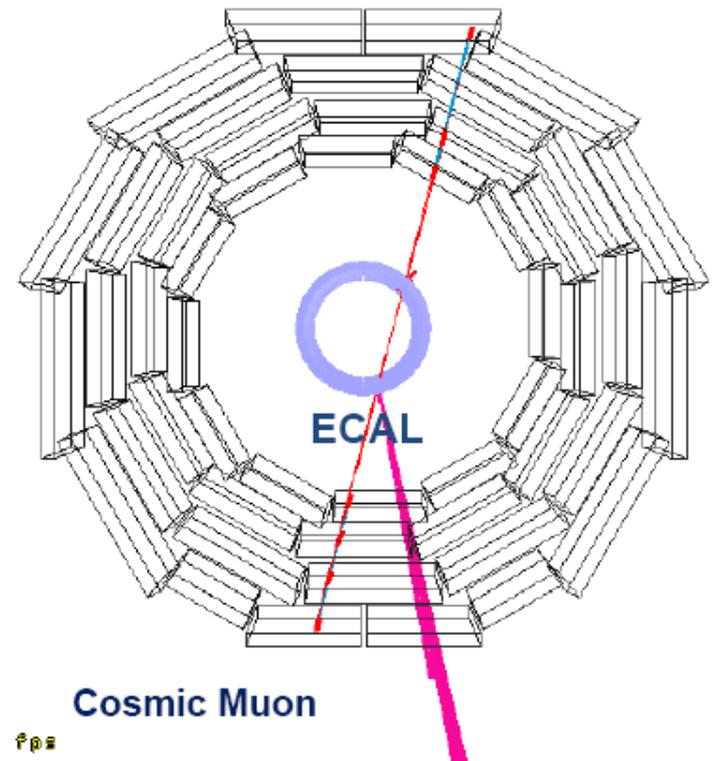
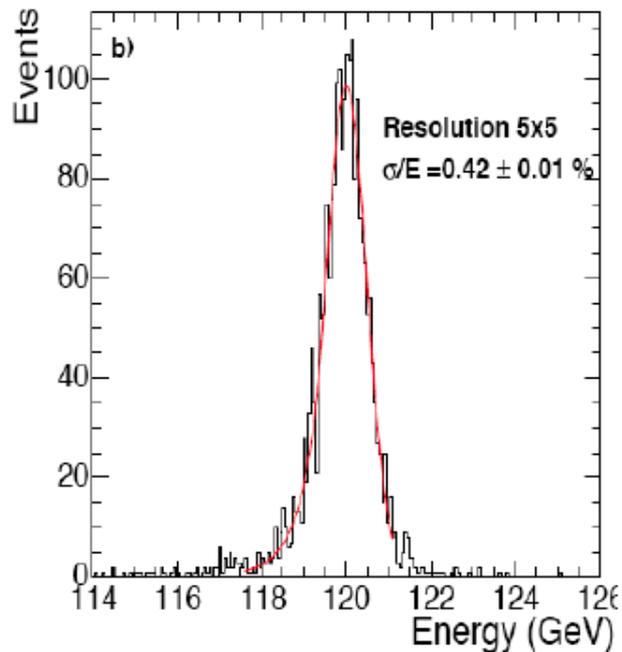


# Электромагнитный калориметр CMS на кристаллах

- *Размеры кристалла:*
  - основание 22ммx22мм*
  - длина 230 мм*
- *Количество кристаллов:*
  - 61 200 в центральной части*
  - 7 324 в торцевых частях*
- *80% света выделяется за 25 нс, но при световом выходе 30 фотонов/МэВ*

# Трек космического мюона в электромагнитном калориметре CMS *CMS crystal em calorimeter*

Response to high energy electrons



17.4/10.2 fps

Temperature Stability:  $\leq 0.1 \text{ }^\circ\text{C}$   
Light response stability:  $\leq 0.1\%$

Data taken in the Underground Cavern

# Модули ЭМ калориметра ATLAS

с продольной и поперечной сегментацией для  
центральной и торцевой частей

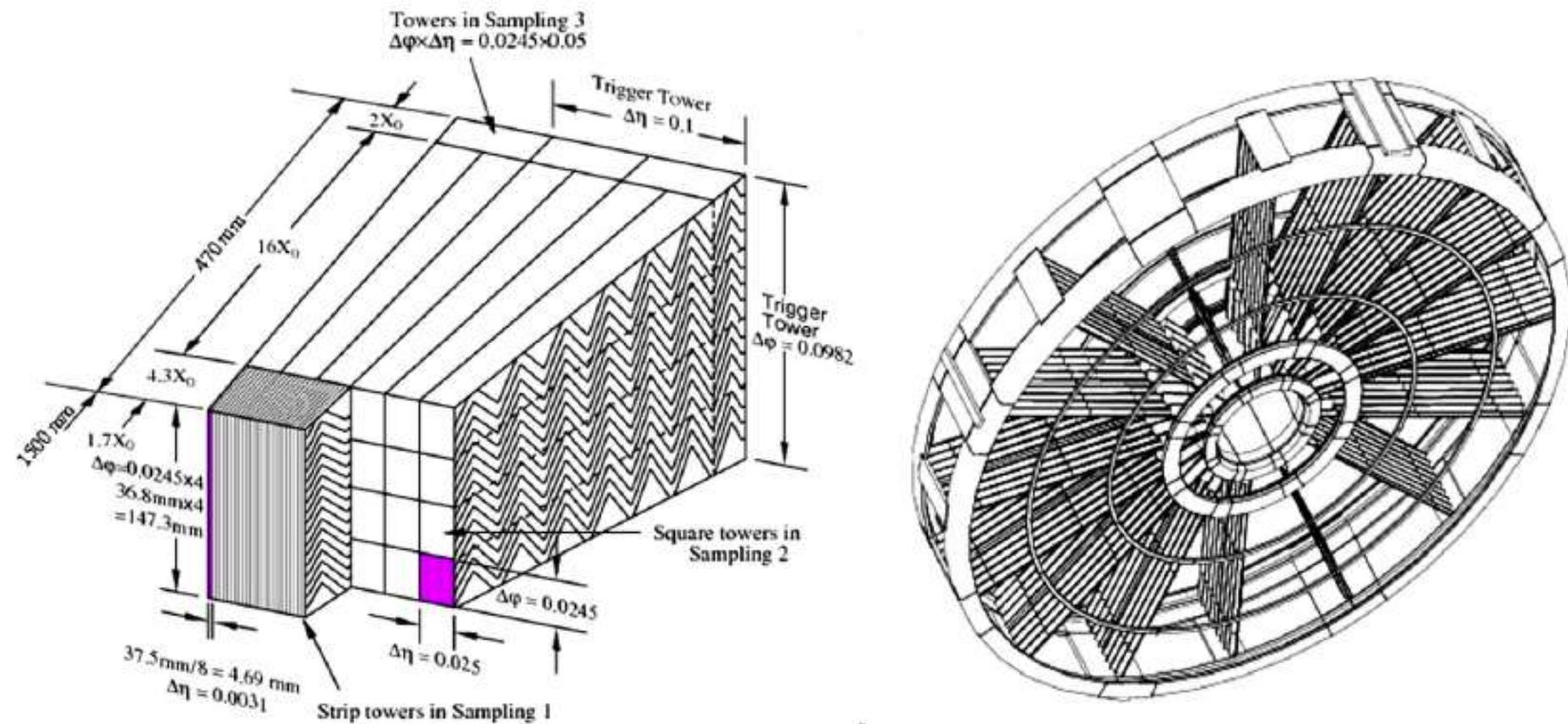


Fig. 2. Left: projective view of the EM module showing the longitudinal and lateral segmentation. Right: schematic view of the EM end-cap wheel.

# Элементы жидкоаргоновой калориметрии ATLAS

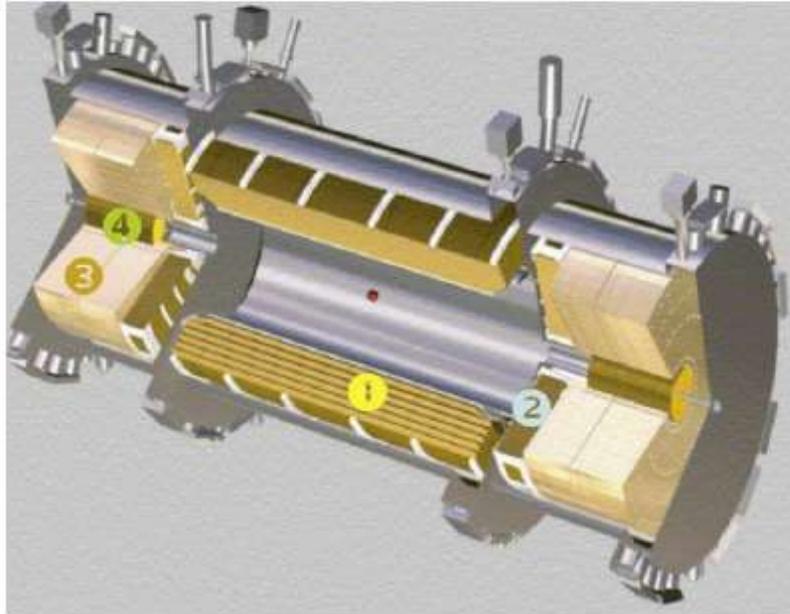


Fig. 1. The ATLAS Liquid Argon Calorimeter: (1) the EM barrel; (2) the EM end-cap; (3) the hadronic end-cap; (4) the forward calorimeter.

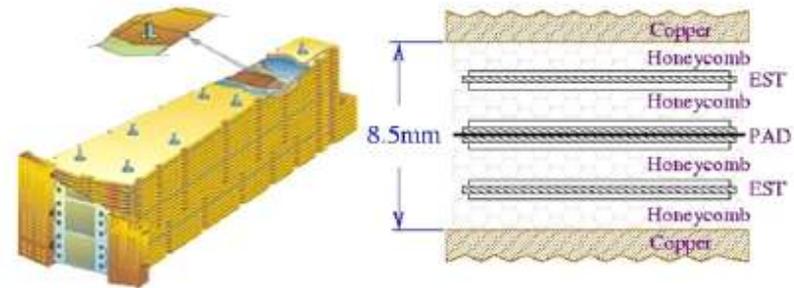


Fig. 3. Schematic view of the HEC module (left), and the gap between the two absorber plates.



Fig. 7. Top left: 25 modules of the HEC wheel. Top middle: EM half-barrel in its cryostat. Bottom left: the HEC integration in its cryostat

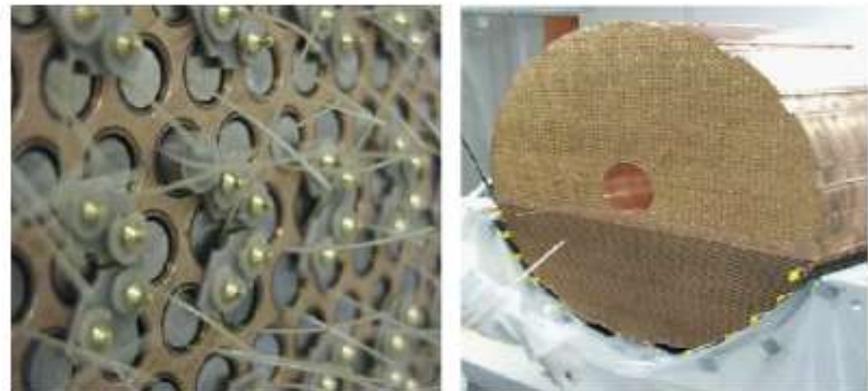
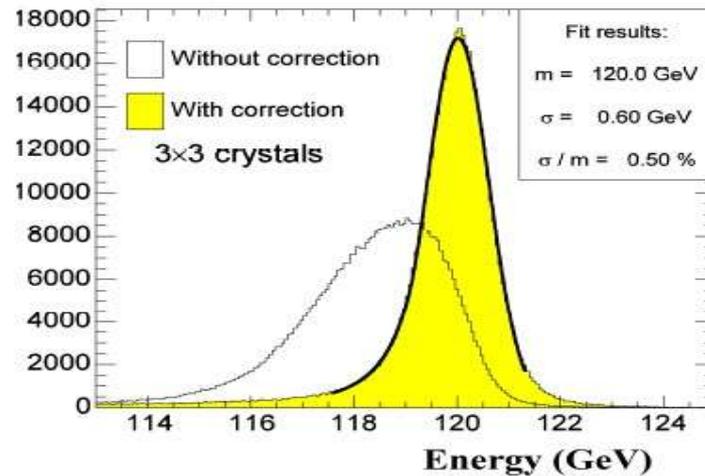
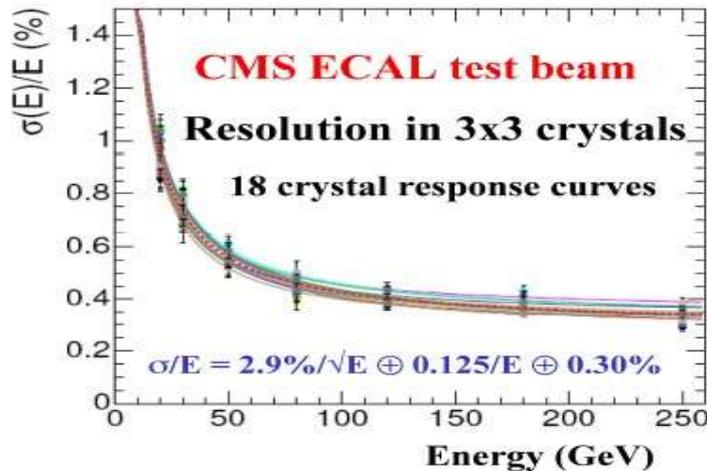
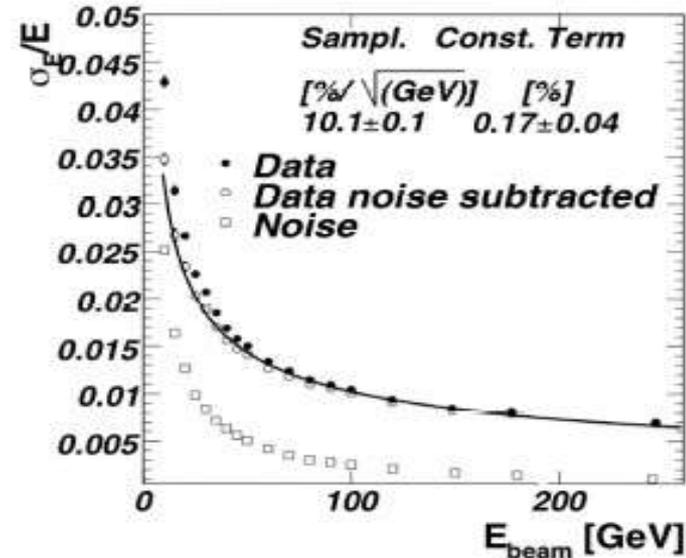
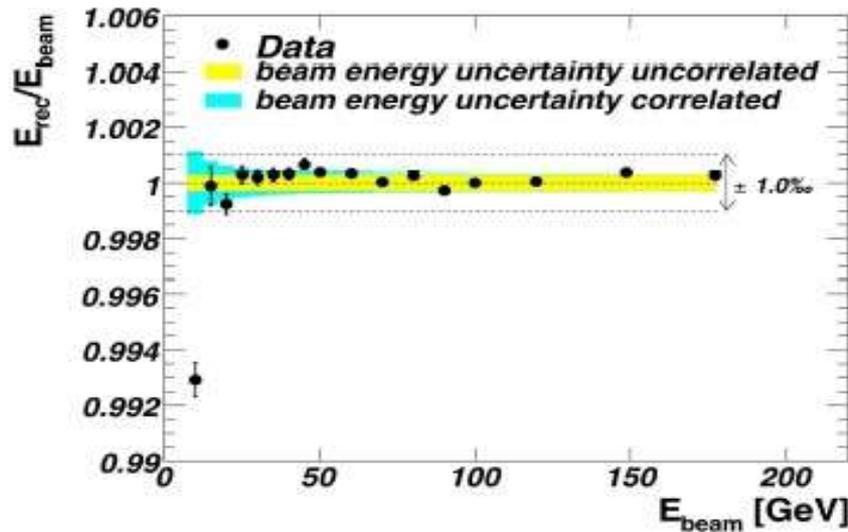


Fig. 4. The face of the electromagnetic FCal module (right).

*175 000 каналов считывания ATLAS LAr EM калориметра*

# ATLAS/CMS: from design to reality

R&D and construction for 15 years → excellent EM calo intrinsic performance



- Stand-alone performance measured in beams with electrons from 10 to 250 GeV

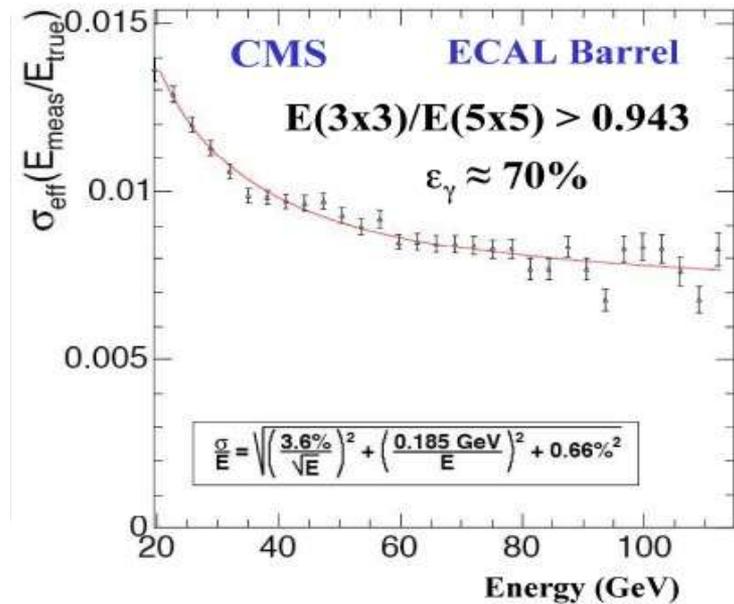
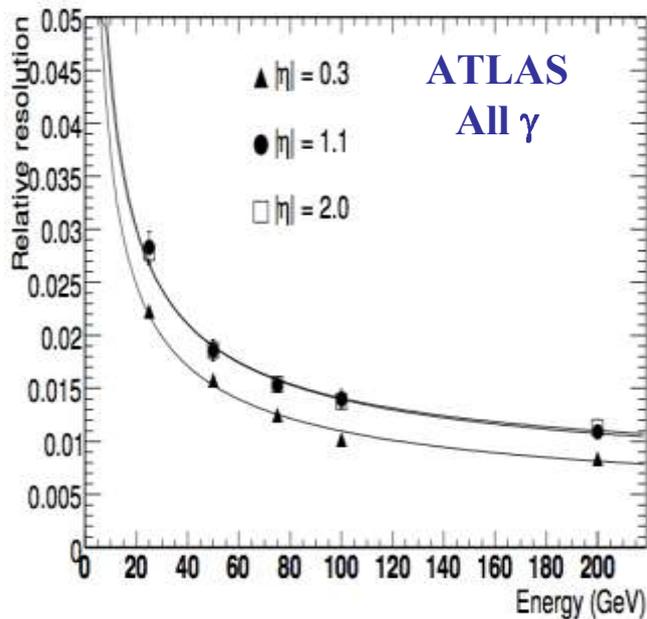
# ATLAS/CMS: from design to reality

Actual performance expected in real detector quite different!!

## Photons at 100 GeV

ATLAS: 1-1.5%  
energy resol. (all  $\gamma$ )

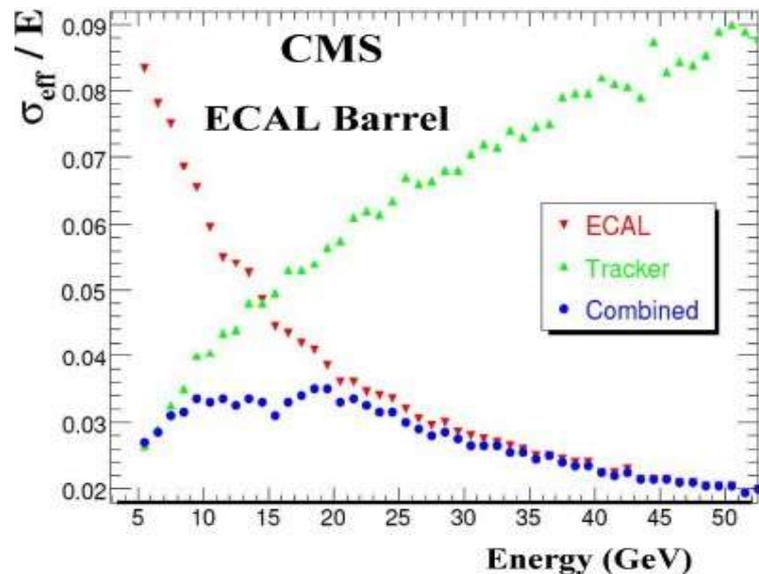
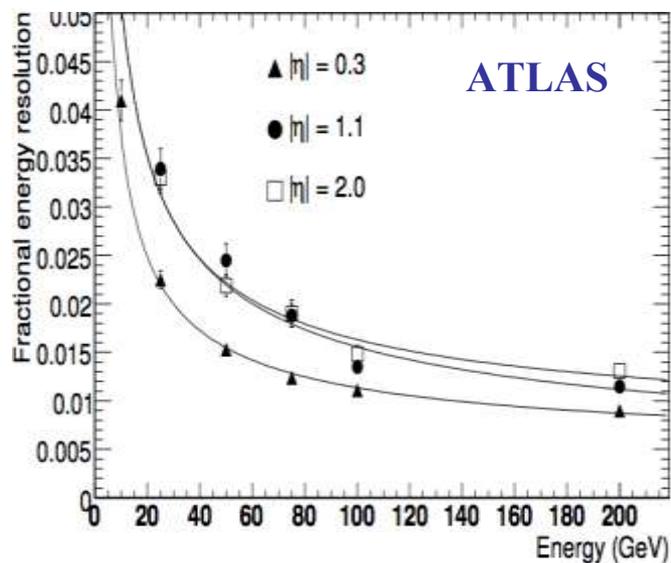
CMS: 0.8%  
energy resol.  
( $\epsilon_\gamma \approx 70\%$ )



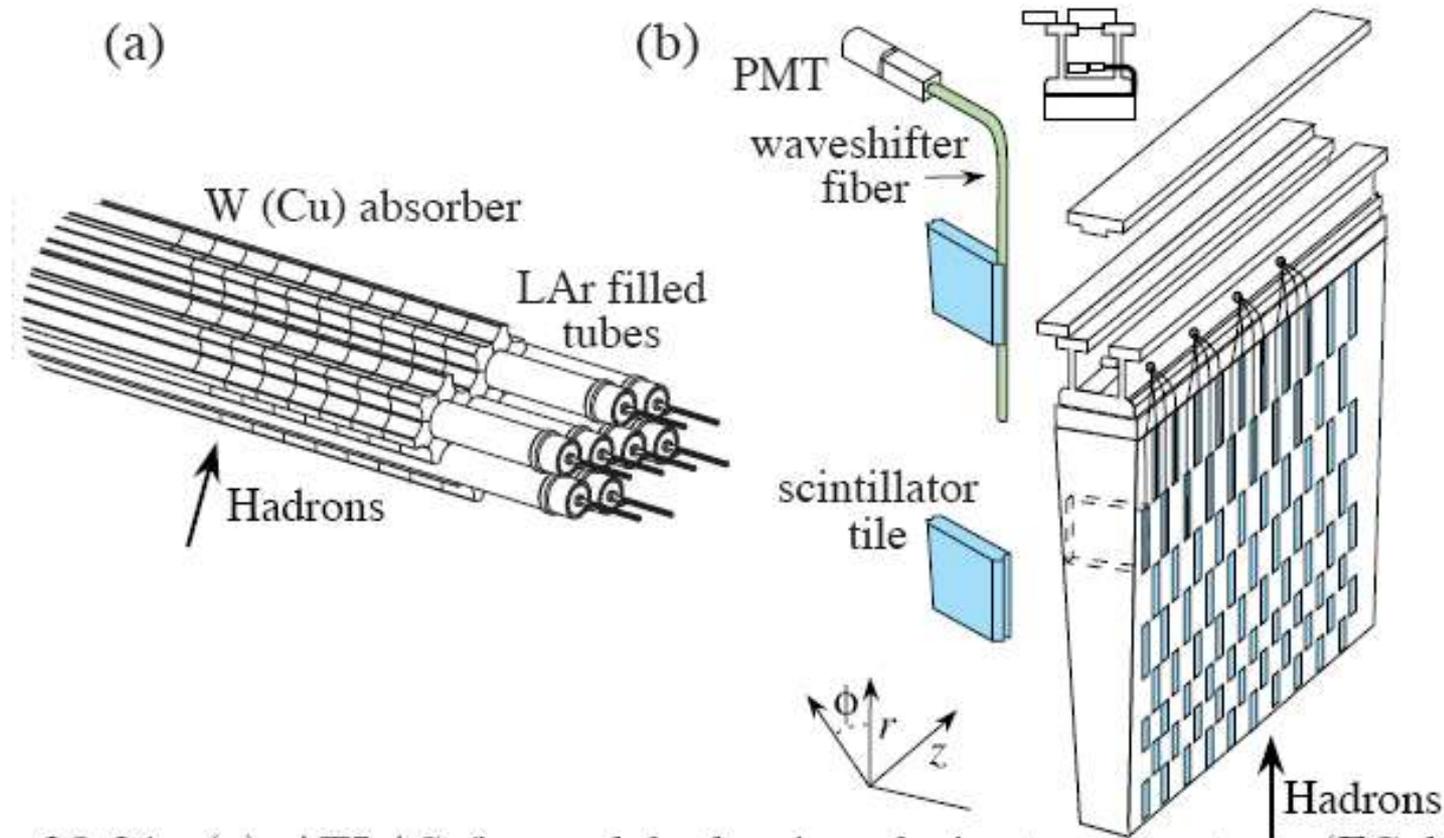
## Electrons at 50 GeV

ATLAS: 1.5-2.5%  
energy resol.  
(use EM calo only)

CMS:  $\sim 2.0\%$   
energy resol.  
(combine EM calo  
and tracker)



# Модули Переднего (а) и Тайл (б) - калориметров ATLAS



**Figure 28.21:** (a) ATLAS forward hadronic calorimeter structure (FCal2, 3). Tubes containing LAr are embedded in a mainly tungsten matrix. (b) ATLAS central calorimeter wedge; iron with plastic scintillator tile with wavelength-shifting fiber readout.

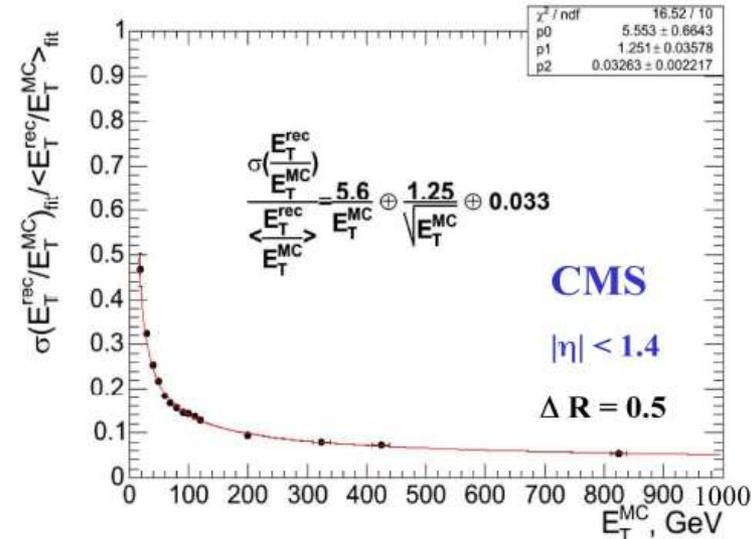
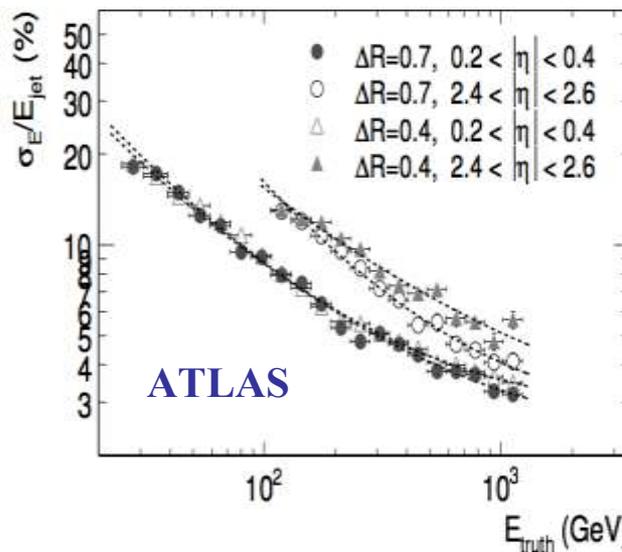
# ATLAS/CMS: from design to reality

Biggest difference in performance perhaps for hadronic calo

## Jets at 1000 GeV

ATLAS ~ 3%  
energy resolution

CMS ~ 5%  
energy resolution,  
(but expect sizable  
improvement  
using tracks at low  
energies)

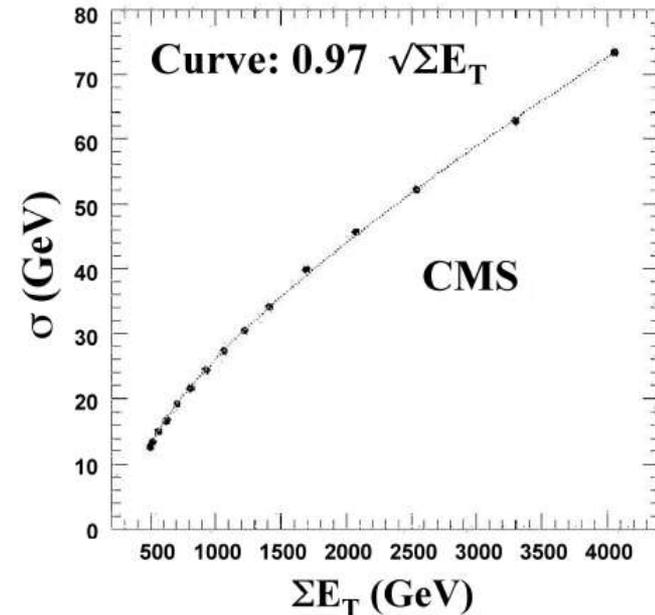
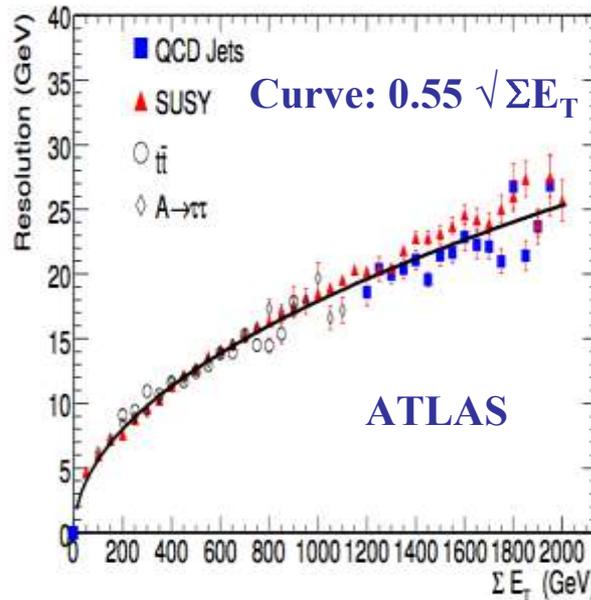


$E_T^{miss}$  at  $\Sigma E_T = 2000$  GeV

ATLAS:  $\sigma \sim 25$  GeV

CMS:  $\sigma \sim 40$  GeV

This may be important  
for high mass H/A to  $\tau\tau$



# Достижения составной калориметрии

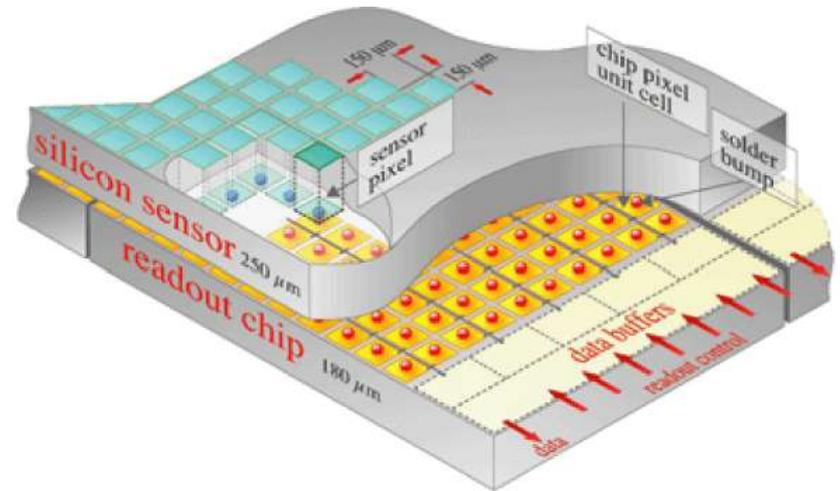
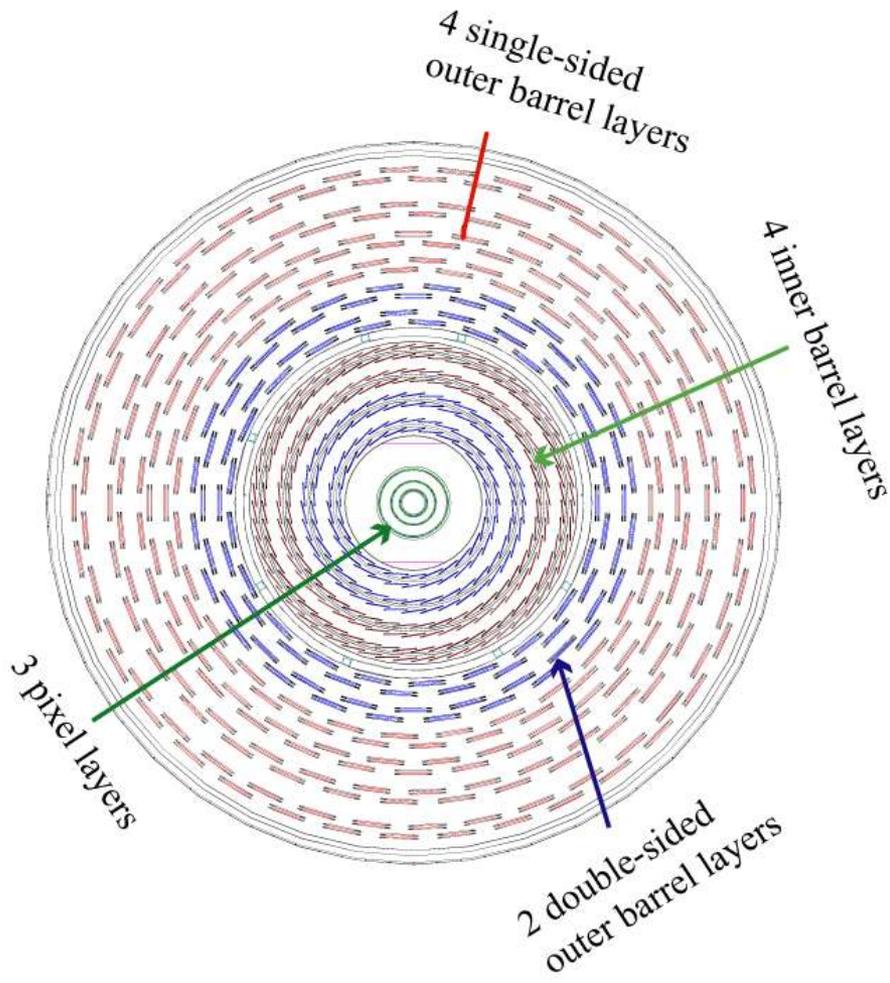
- Успех в создании калориметров обусловлен технологическим прорывом в производстве
  1. *сцинтилляторов (метод литья под давлением в пресс-формы)*
  2. *штамповки стальных листов радиатора для ATLAS, LHCb*
- *Поперечное положение пластин имеет преимущества:*
  1. *достигается однородность и механическая прочность*
  2. *Поперечная толщина радиатора порядка или меньше X0*
  3. *Упрощает внедрение средств калибровки: стальных трубок с гидравлическим приводом радиоактивного источника без создания нечувствительных зон*
- *Использование оптических волокон для сбора и передачи света*
- *Составные и непрерывные электромагнитные калориметры демонстрируют сравнимые параметры*
- *Все эти достижения будут использованы в будущих установках*

# *Трековые системы ATLAS и CMS: предельные параметры составляют*

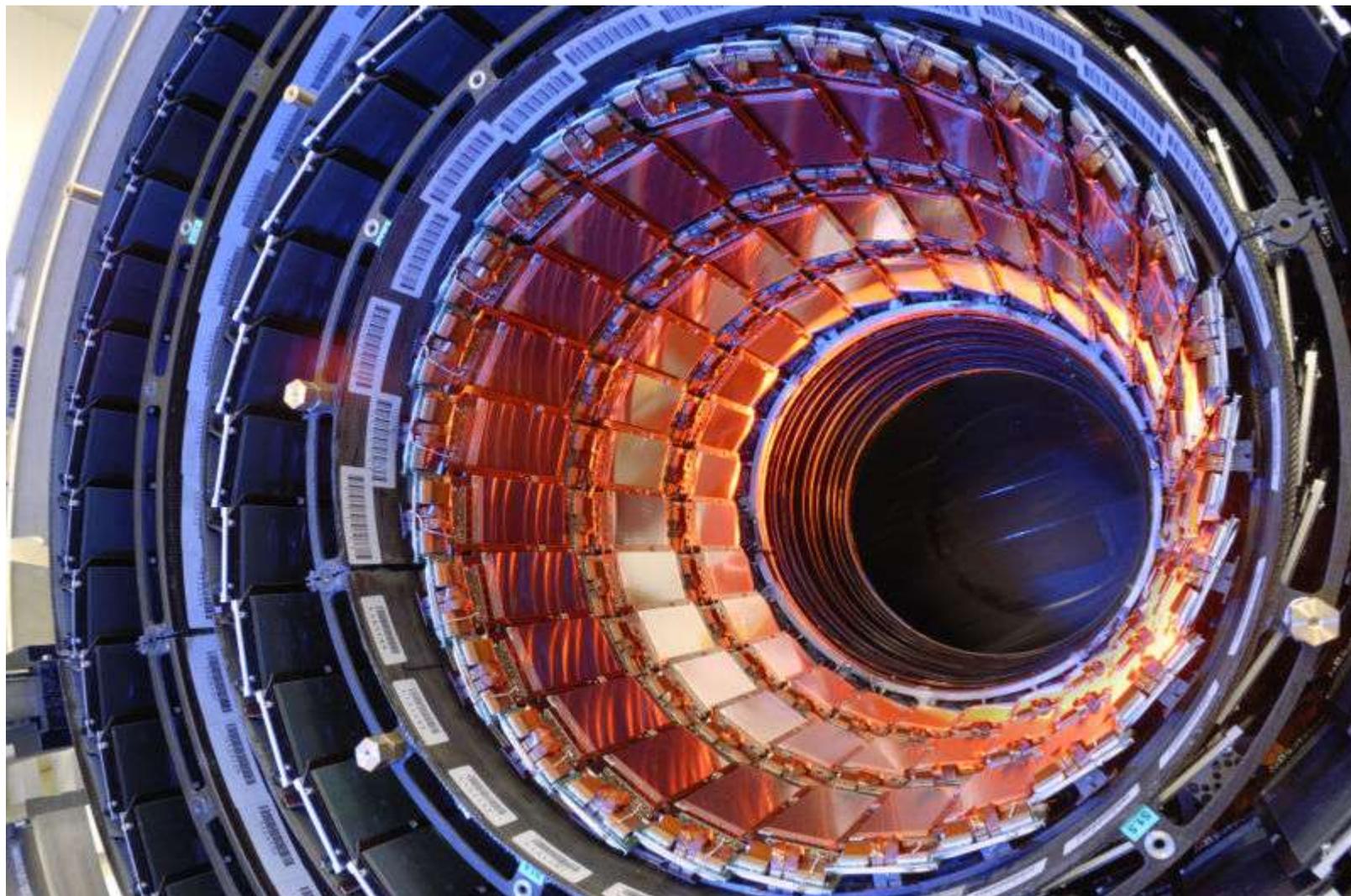
- 80 млн. каналов считывания пиксельных детекторов вблизи области соударения в ATLAS
- 205 м<sup>2</sup> микростриповых кремниевых детекторов в треkere CMS и 76 млн. каналов – самый большой кремниевый детектор в мире

# Трекер CMS

- Состоит из 13 слоев в центральной части и 14 слоев в торцевых частях
- Три слоя пикселей до радиуса 11 см с площадью сенсора  $100 \times 150$  мкм считывают 66 млн. каналов



# *Кремниевый трекер CMS*



# Внутренний детектор АТЛАС

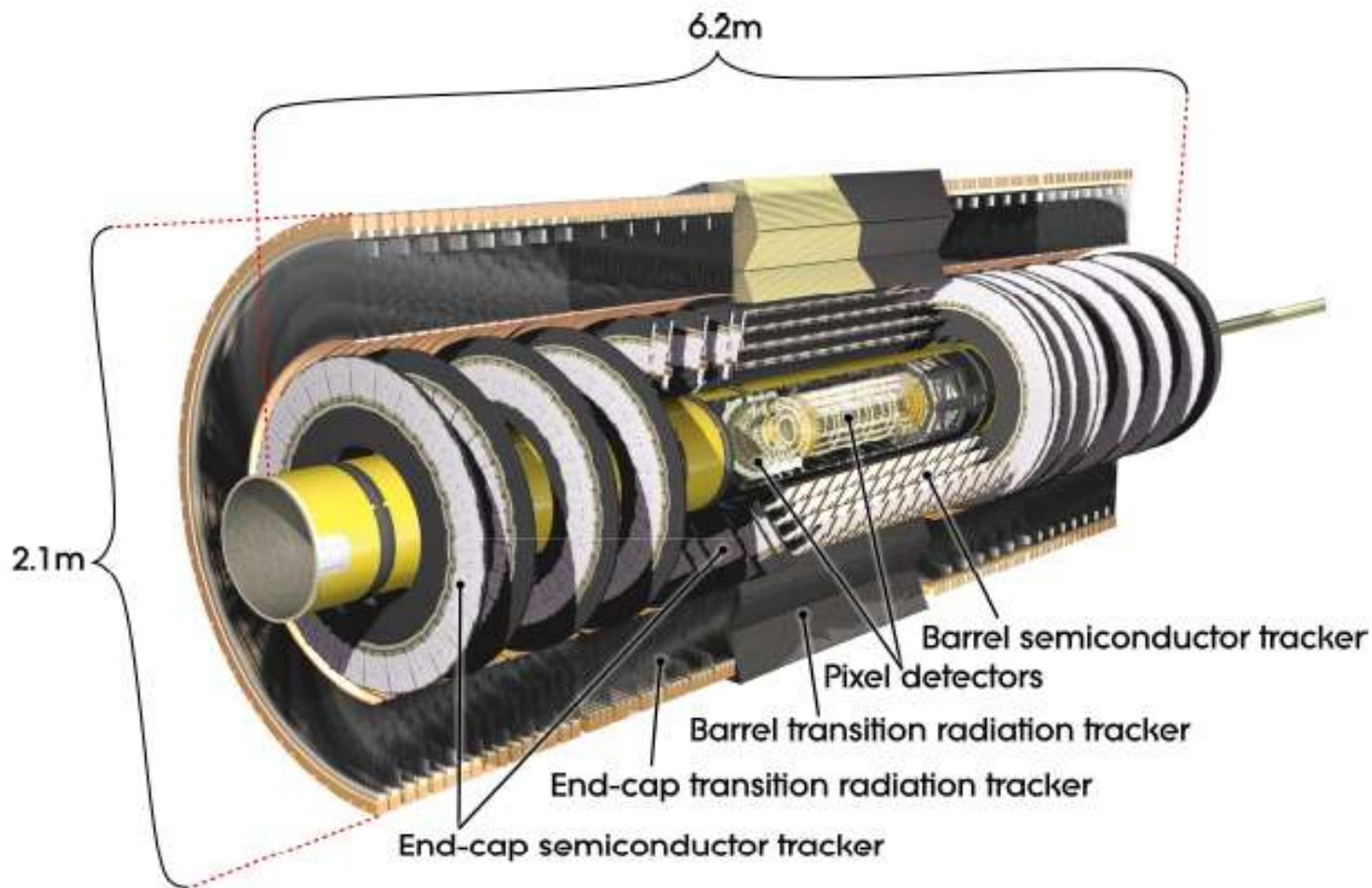
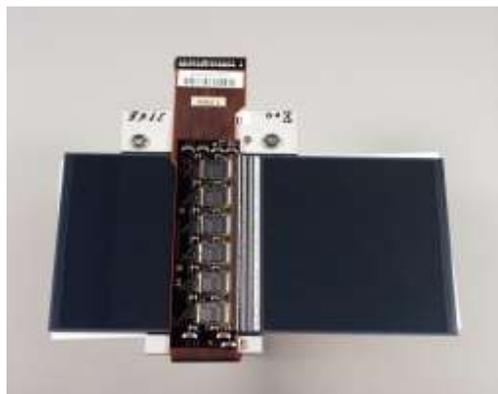
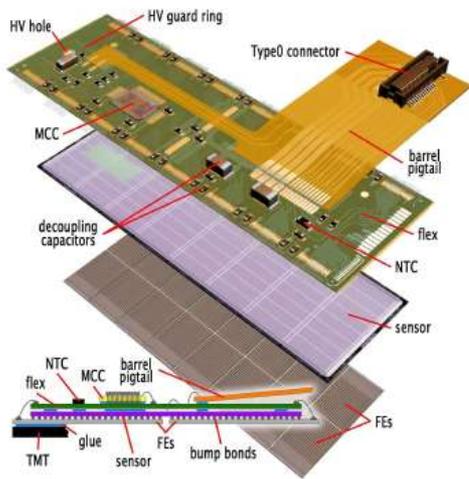


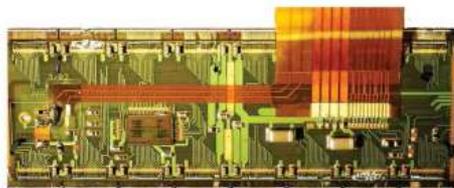
Figure 2. The ATLAS inner detector.

# Элементы Внутреннего детектора ATLAS



Module type	Sensor type	Cut length (mm)	Outer width (mm)	Inner width (mm)	Strip pitch ( $\mu\text{m}$ )	Inter-strip angle ( $\mu\text{rad}$ )
Barrel	Barrel	63.960	63.560	63.560	80.0	0
End-cap inner	W12	61.060	55.488	45.735	56.9–69.2	207.0
End-cap middle	W21	65.085	66.130	55.734	69.9–83.0	207.0
End-cap outer	W22	54.435	74.847	66.152	83.4–94.2	207.0
	W31	65.540	64.635	56.475	70.9–81.1	161.5
	W32	57.515	71.814	64.653	81.5–90.4	161.5

**Table 11.** External cut dimensions of the SCT barrel and end-cap (EC) sensors. The tolerance on all external dimensions is  $\pm 25 \mu\text{m}$ ; the mask accuracy is at the level of  $\pm 1 \mu\text{m}$ . The inter-strip angle is that between adjacent strips of the sensor. The sensors are fabricated from 4-inch wafers.



**Figure 31.** Schematic view of a barrel pixel module (top) illustrating the major pixel hybrid and sensor elements, including the MCC (module-control chip), the front-end (FE) chips, the NTC thermistors, the high-voltage (HV) elements and the Type0 signal connector. Also shown (middle) is a plan view showing the bump-bonding of the silicon pixel sensors to the polyimide electronics substrate. The photograph at the bottom shows a barrel pixel module.

# Схема прохождения трека частицы с импульсом 10 ГэВ во Внутреннем детекторе ATLAS

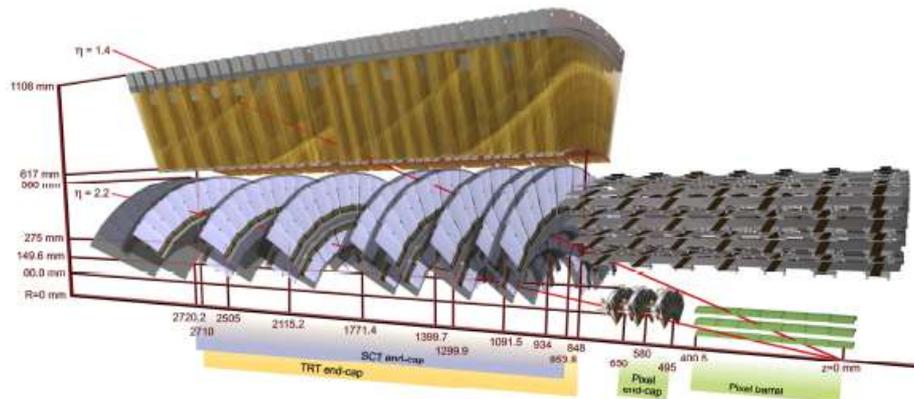
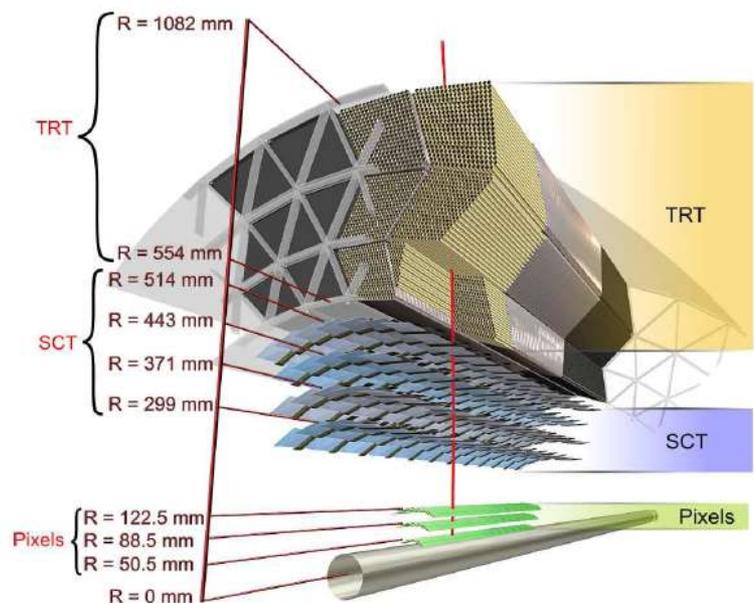
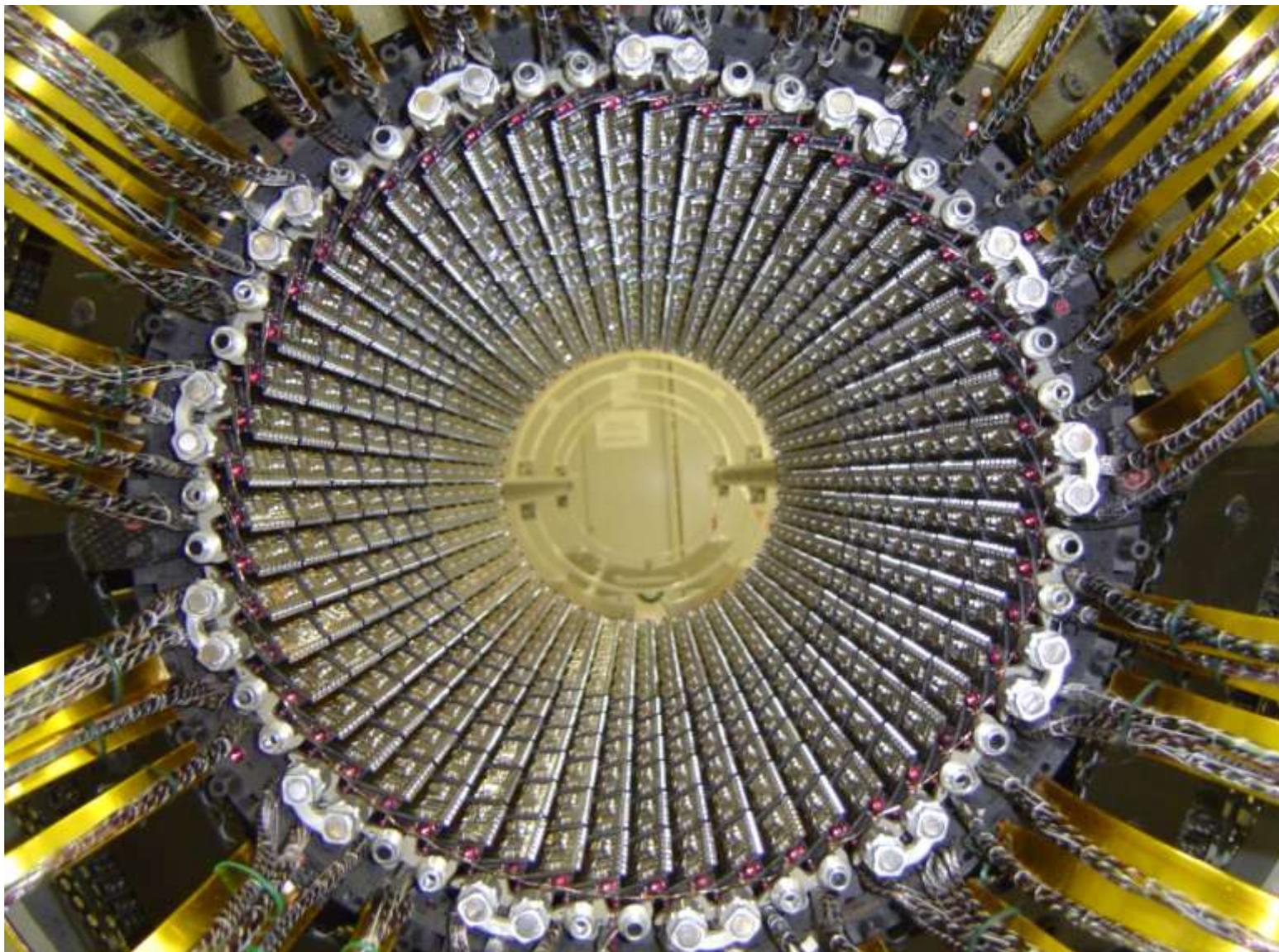


Table 1  
Layout parameters of SCT barrel and endcap detector

	SCT barrel	SCT endcaps
Silicon area (m <sup>2</sup> )	34.4	26.7
On	4 Barrels	9 Disks/endcap
Channel number (10 <sup>6</sup> )	3.2	3.0
Number of modules	2112	1976
$r\phi$ Resolution ( $\mu\text{m}$ )	16	16
$z$ Resolution ( $\mu\text{m}$ )	580	580
Pseudo-Rapidity	$ \eta  < \approx 1.2$	$\approx 1.2 <  \eta  < 2.5$
Coverage		
Radial coverage (mm)	$300 < r < 520$	$300 < r < 520$

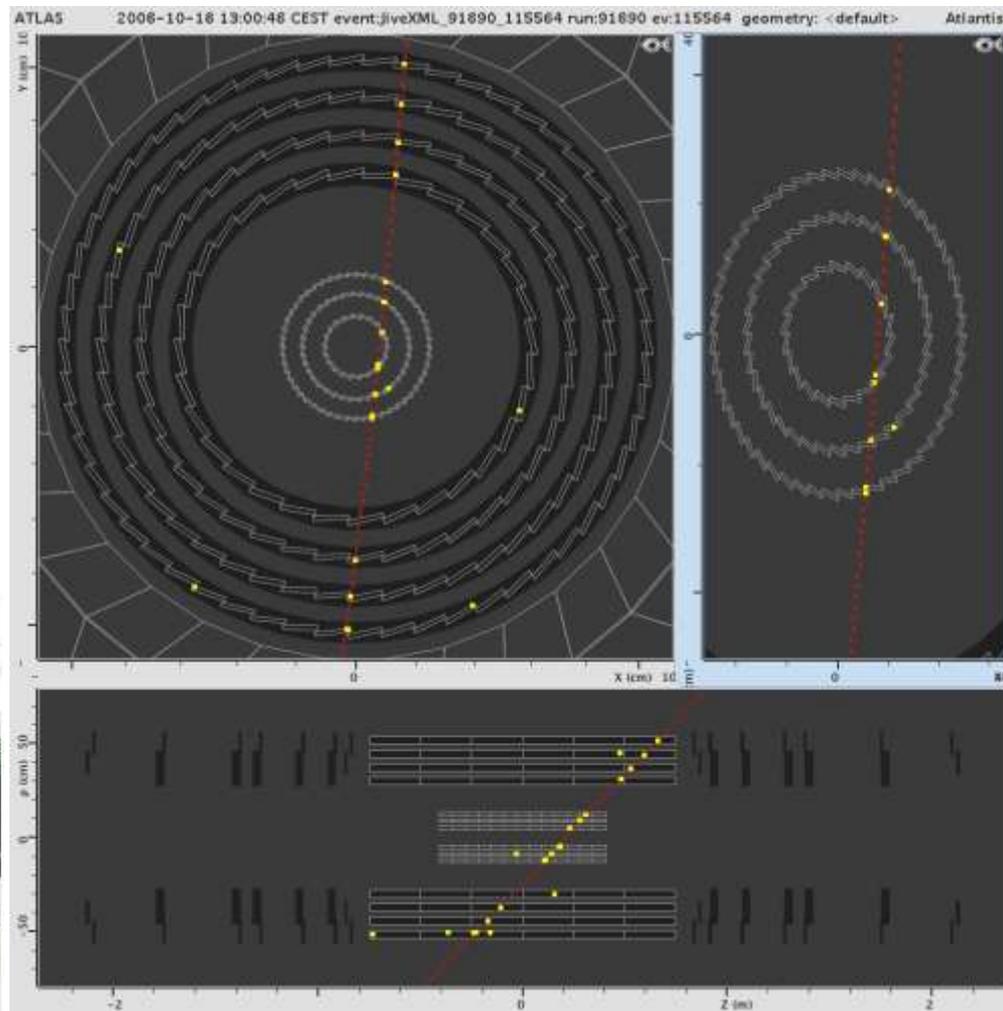
Figure 29. Drawing showing the sensors and structural elements traversed by a charged track of 10 GeV  $p_T$  in the barrel inner detector ( $\eta = 0.3$ ). The track traverses successively the beryllium beam-pipe, the three cylindrical silicon pixel layers with individual sensor elements of  $50 \times 400 \mu\text{m}^2$ , the four cylindrical double layers (one axial and one with a stereo angle of 40 mrad) of barrel silicon microstrip sensors (SCT) of pitch  $80 \mu\text{m}$  and approximately 36 axial straws of 4 mm diameter contained in the barrel transition radiation tracker modules within their support structure.

# *Пиксели АТЛАС*

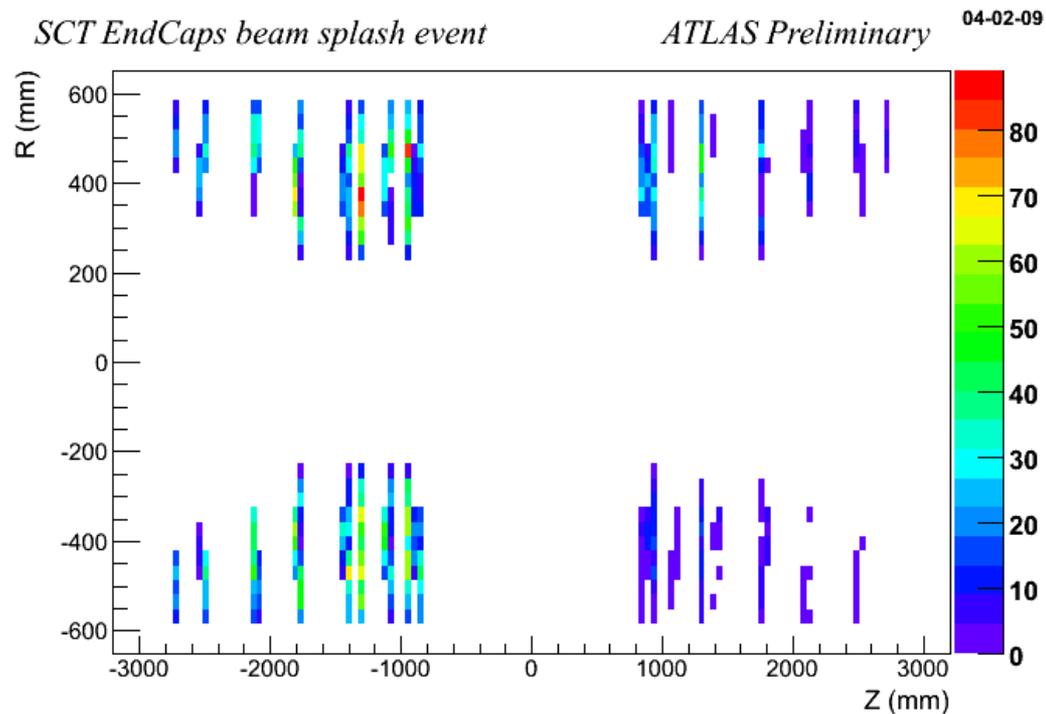
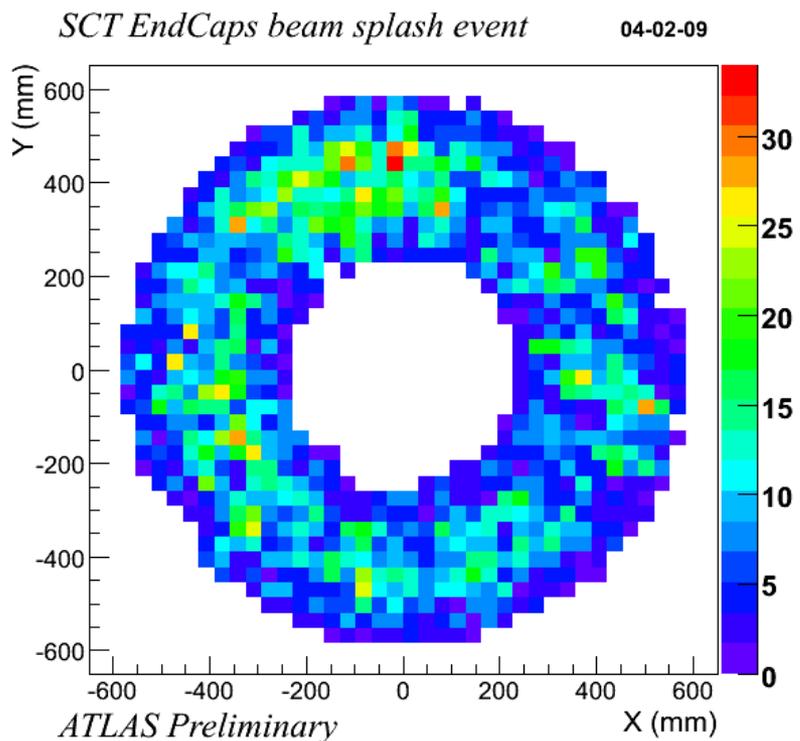


# Регистрация космических мюонов в ATLAS

Прохождение космического мюона через полупроводниковый трекер ATLAS: SCT+Pixel, Pixel только (справа)  
Виден всего один сигнал шума  
Вершинный детектор LHCb

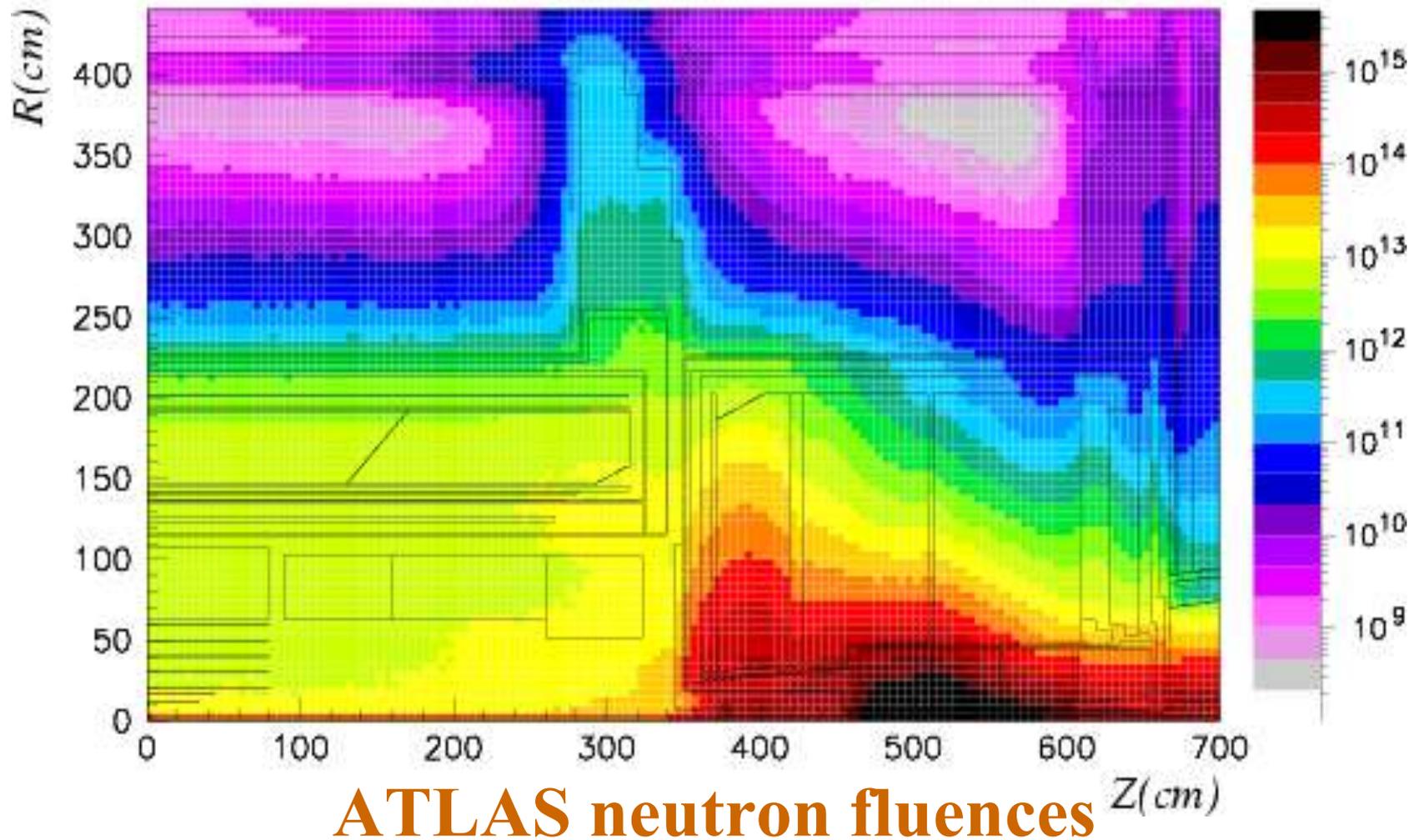


# Отклик на выброс частиц по направлению пучка в ATLAS



# Радиационные условия

(1 MeV  $n_{eq}/cm^2/yr$ )



# Мюонные спектрометры: газовые дрейфовые камеры

## ATALS

- MDT –1150

5500 кв.м

- CSC - 32

- TGC

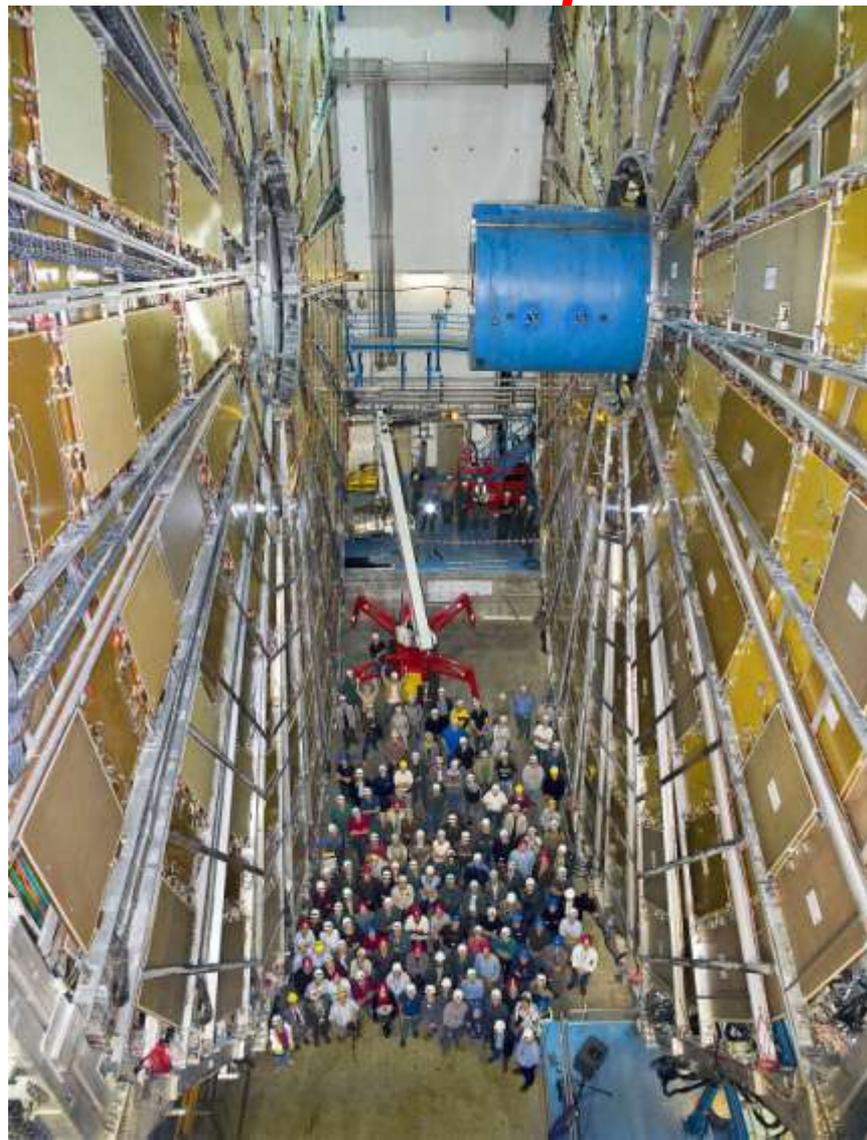
- RPC

## CMS

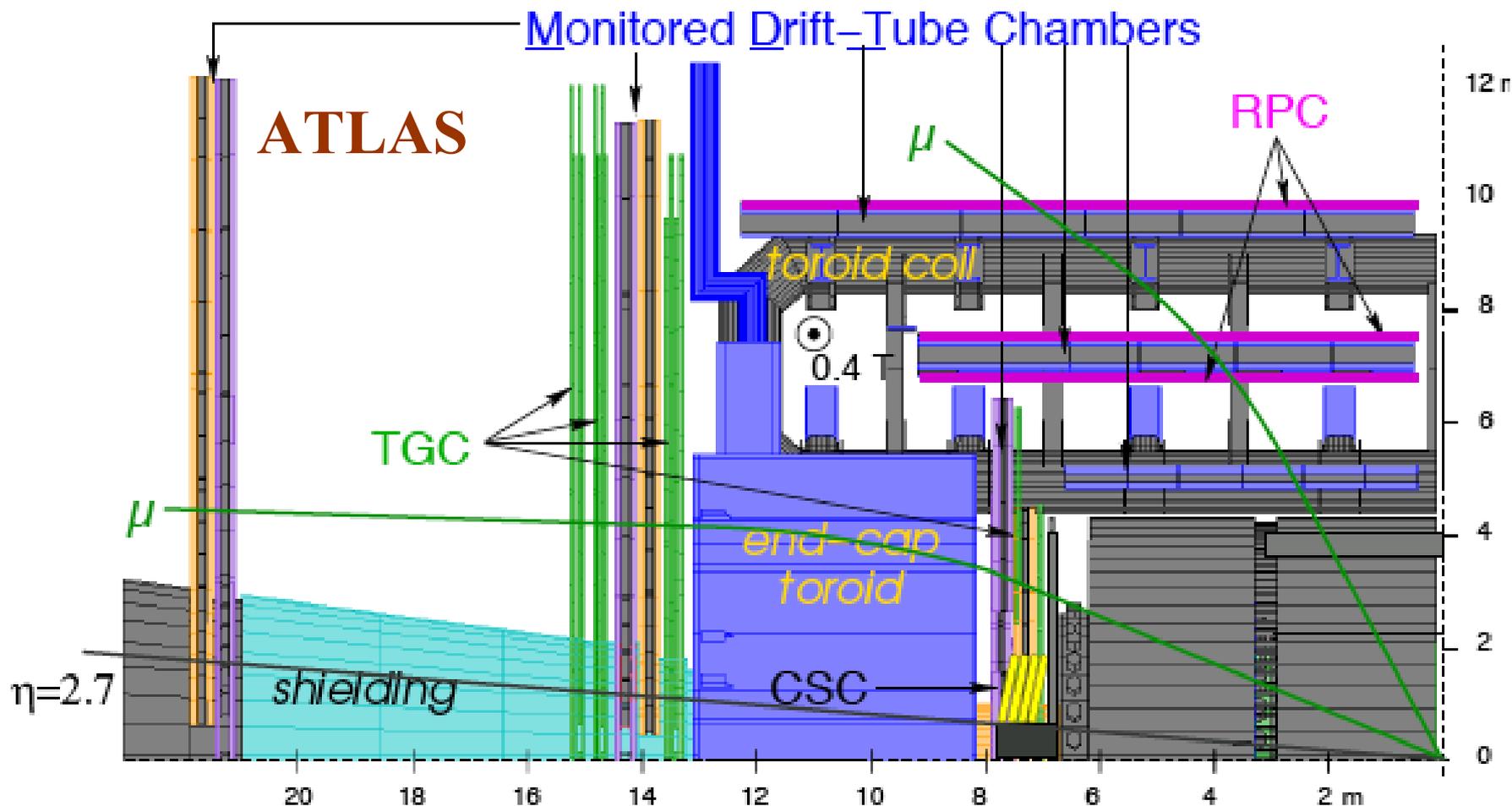
- DT

- CSC

- RPC



# ATLAS/CMS: from design to reality



## ATLAS muon spectrometer

- Excellent stand-alone capabilities and coverage in open geometry
- Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential  $\eta \times \phi$  coverage ( $|\eta| < 2.7$ ))

# Прецизионные камеры ATLAS

## The ATLAS Muon Spectrometer

- **ATLAS muon spectrometer:**

1150 **MDT** (monitored drift tube) and 32 **CSC** (cathode strip chamber) high-precision muon tracking chambers

2 × 3 or 2 × 4 tube layers,  $d = 30$  mm,  $L = 0.9\text{--}6.2$  m, 5500 m<sup>2</sup> covered area

measure momentum **stand-alone** to  $\Delta p_T/p_T = 10\%$  at  $p_T = 1$  TeV, i.e.

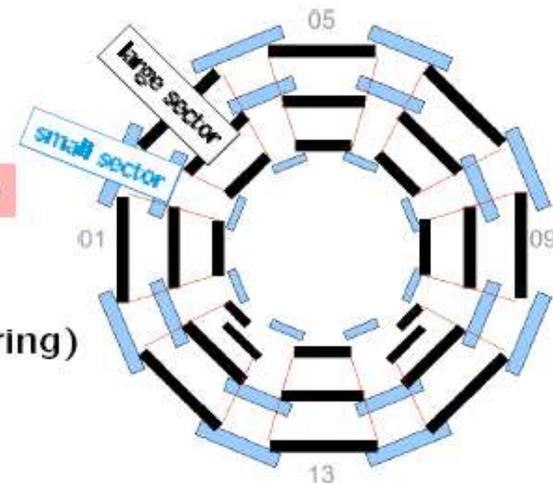
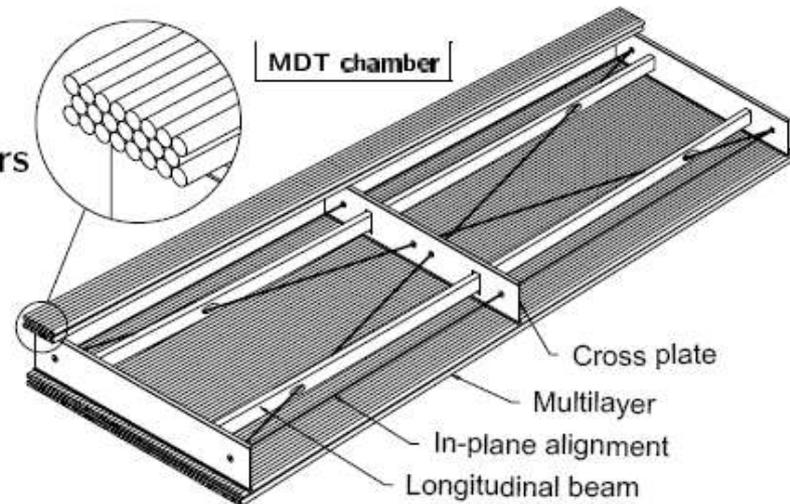
measure **sagitta** of 500  $\mu\text{m}$  with an **accuracy** of 50  $\mu\text{m}$

for this you need:

- high intrinsic resolution of tubes (80  $\mu\text{m}$ )
- accurately placed tubes in a chamber (20  $\mu\text{m}$ )
- good knowledge of chamber positions (30–40  $\mu\text{m}$ )

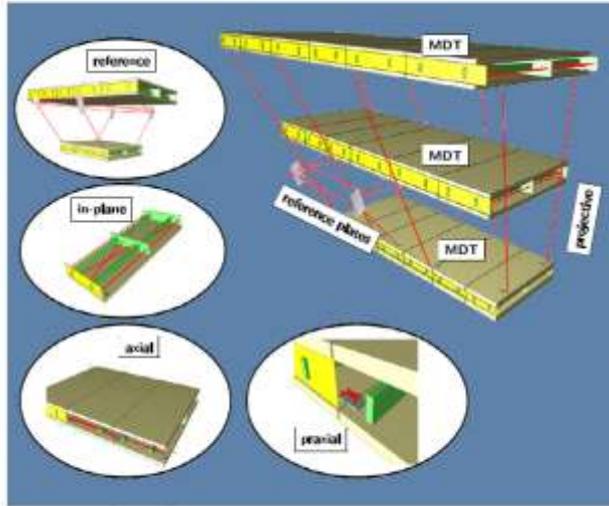
→ **alignment system** to continuously measure muon chamber positions and deformations during ATLAS data-taking (no adjustment, only monitoring)

based on **optical sensors** (to measure positions) and **temperature sensors** (to deduce expansion)



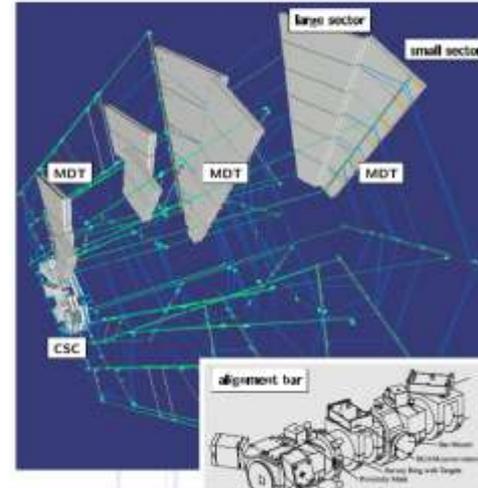
# Система коррекций MC ATLAS

## Alignment System Layout – Barrel



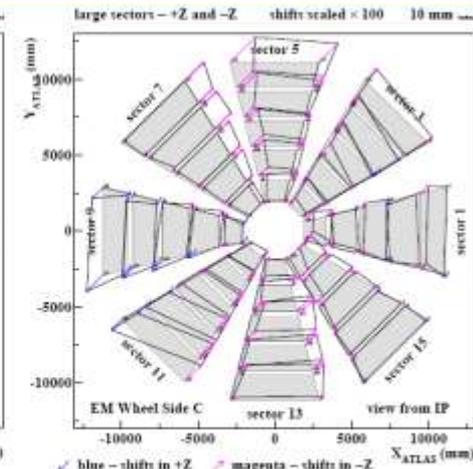
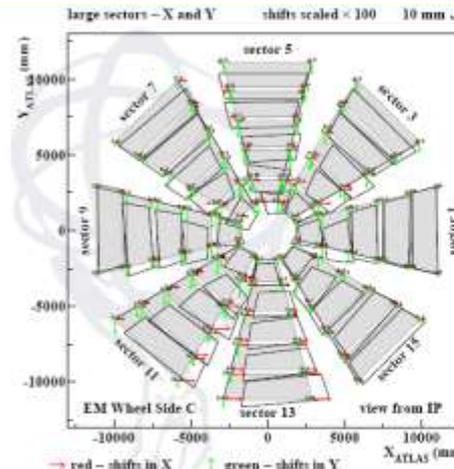
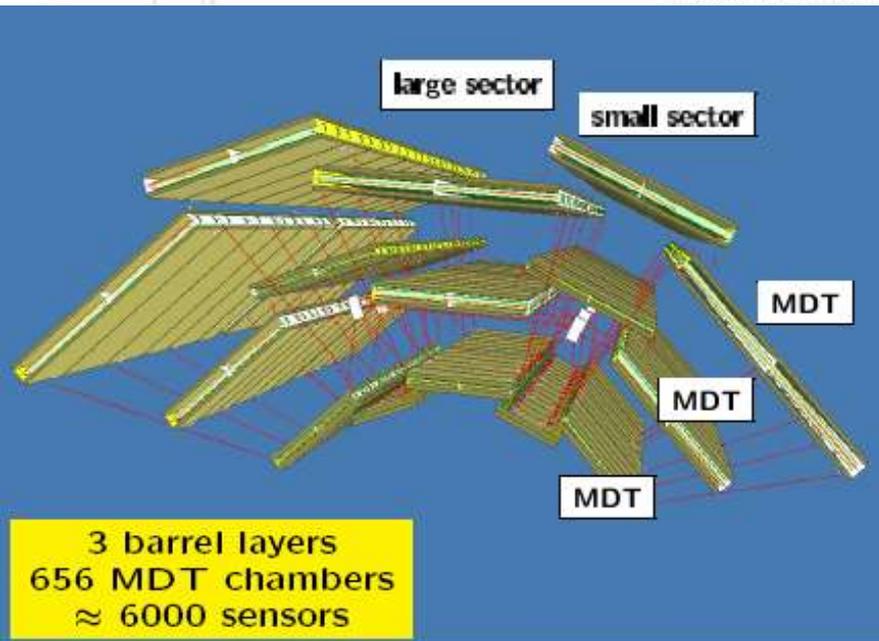
- projective RASNIKS align chambers between layers
- praxial RASNIKS align chambers within a layer
- axial RASNIKS align chambers within a layer
- reference SaCams align chambers between inner layers and between sectors
- in-plane RASNIKS measure chamber deformations
- Temperature sensors measure expansion

## Alignment System Layout – Endcap



- Endcap system elements:
    - BCAM: CCD camera views two laser diodes on another BCAM
    - RASNIK: CCD camera views coded chessboard mask
- Alignment bars: Aluminum tubes,  $L = 1.9-9.6$  m,  $d = 80-85$  mm.

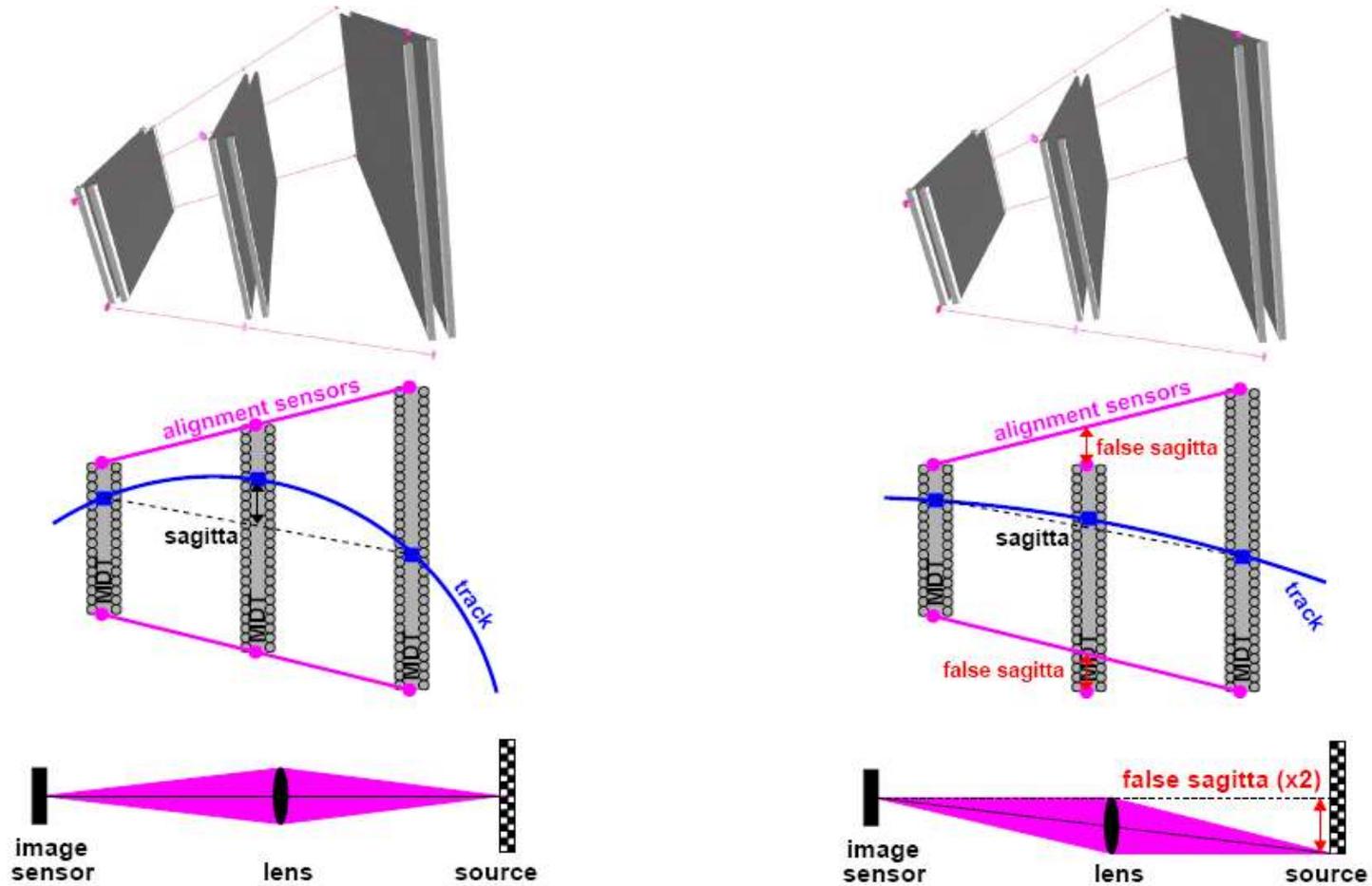
## Alignment Data Analysis



- Alignment result:
  - reconstructed chamber positions, rotations, and deformations – plus diagnostic information (→ next slide)

example: displacements from nominal position in one of the endcap wheels ↑  
 confirmed by survey, chamber distance measurements etc at  $\mathcal{O}(100-500 \mu\text{m})$  level

# Система коррекций MC ATLAS

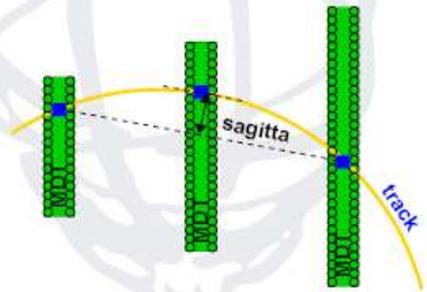


# Масштаб поправок от оптической системы коррекций

## Validation Using Cosmic Muons

- First look at straight tracks in ATLAS:

2008 ATLAS cosmic running  
with magnetic field off –  
 $10^8$  muon-triggered events

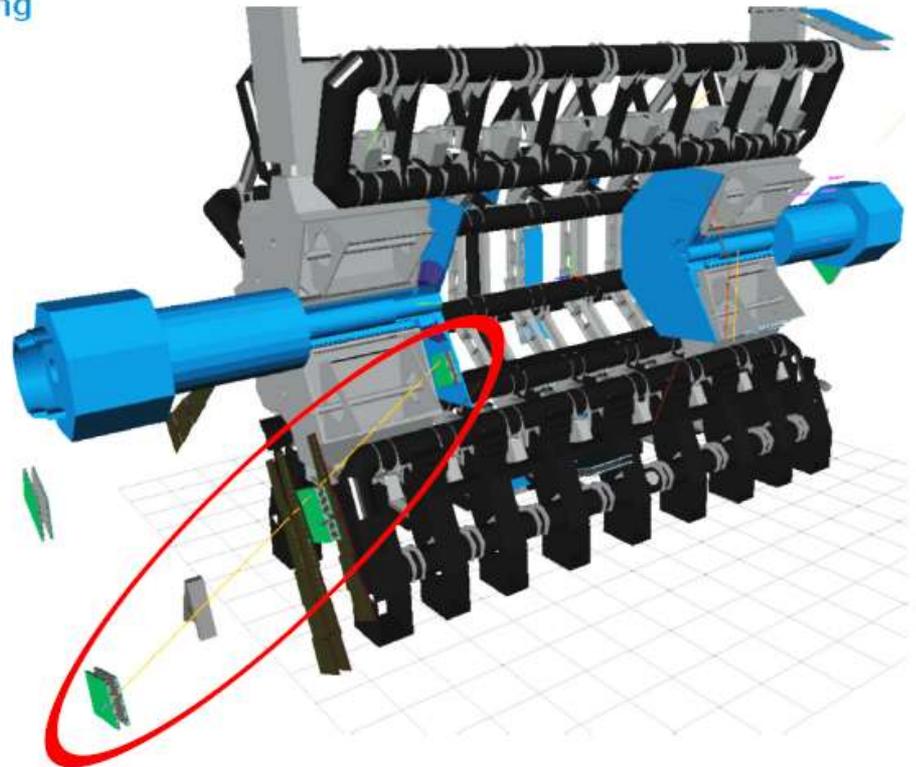


a “gold-plated” event  
run 91351 event 262222

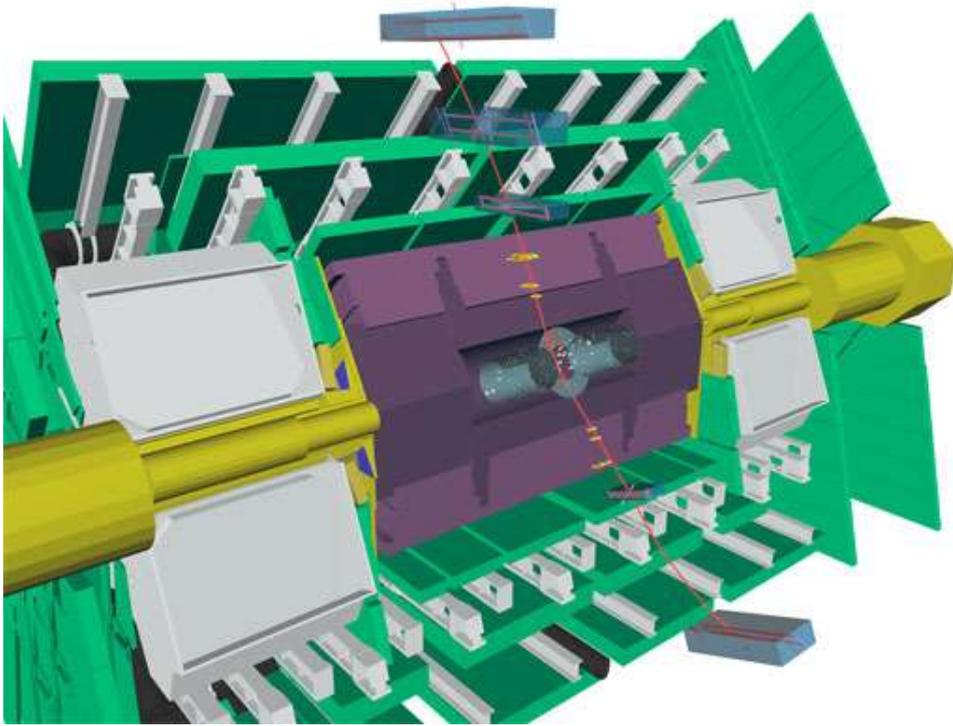
sagitta changes from

- $s = +18448 \mu\text{m}$  to
- $s = -56 \mu\text{m}$

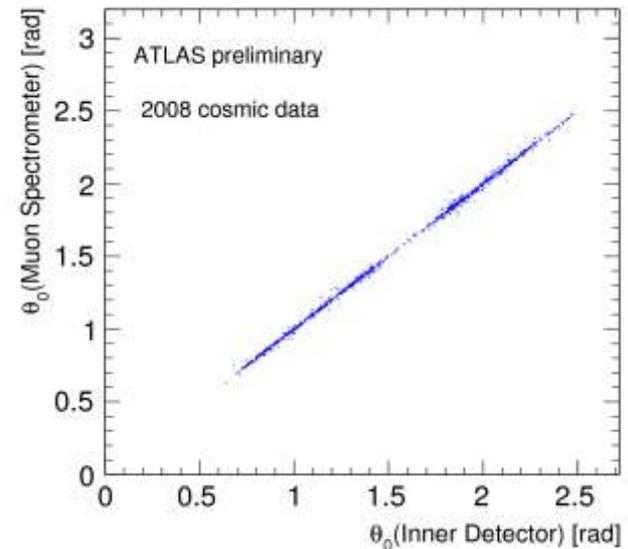
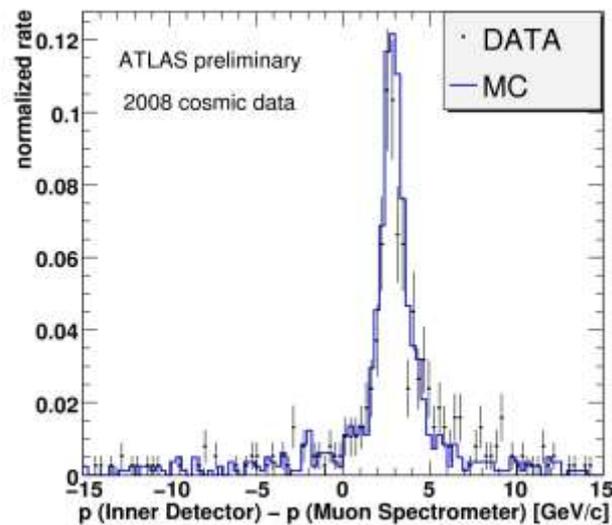
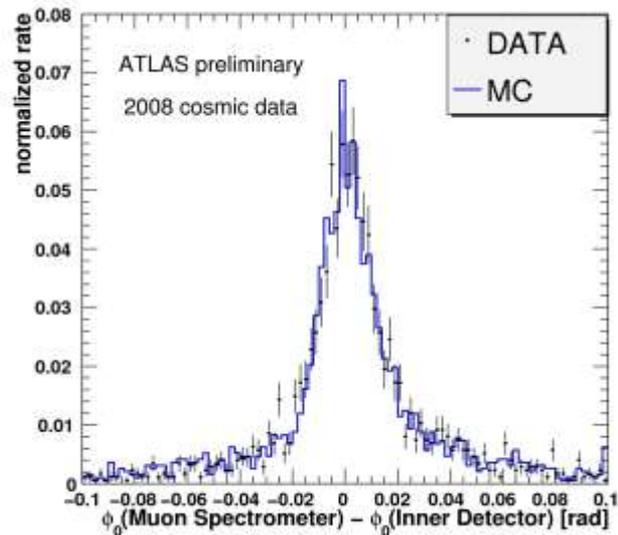
when optical alignment  
corrections are applied



Восстановленный трек  
космического мюона в установке  
АТЛАС при включенных магнитах,  
осень 2008г.



Разности измерений  
пространственного угла  
падения  $\Theta_0$  (слева) и  
импульса  $p$  мюона в МС и ВД  
(точки) в сравнении с  
расчетами Монте-Карло  
(\_\_\_\_)(в центре),  
корреляция при измерении  $\Theta_0$   
в МС и ВД (справа) для  
космических мюонов



# Параметры MC ATLAS

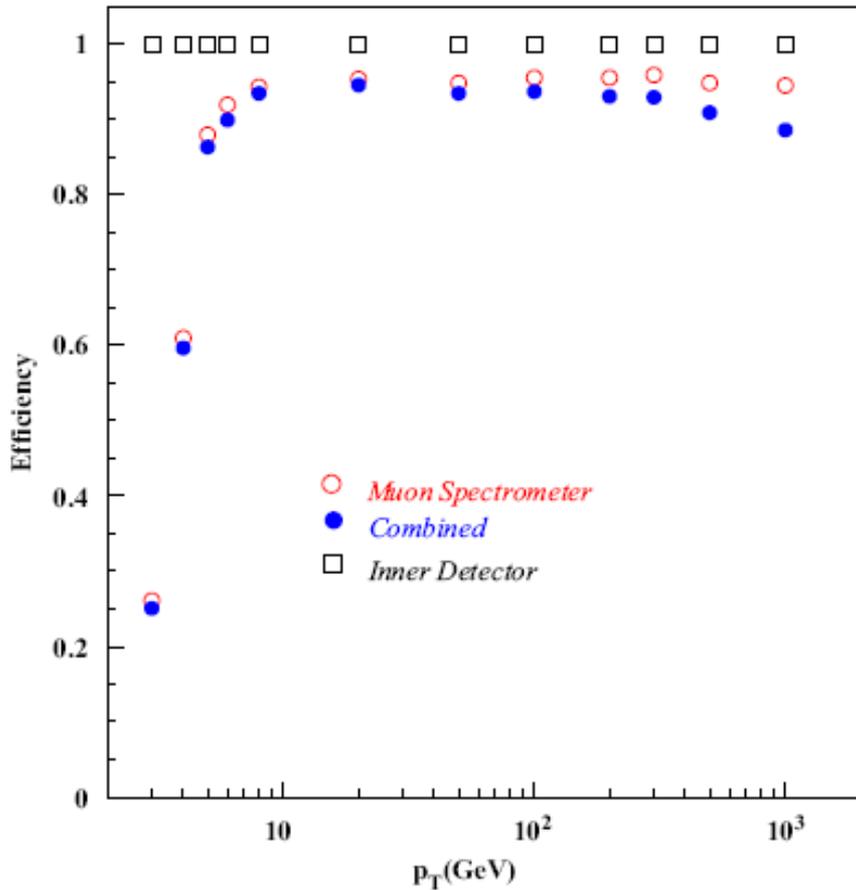


Fig. 2. Efficiency of track reconstruction in the Muon System and in the Inner Detector, using the STACO procedure, as a function of  $p_T$ .

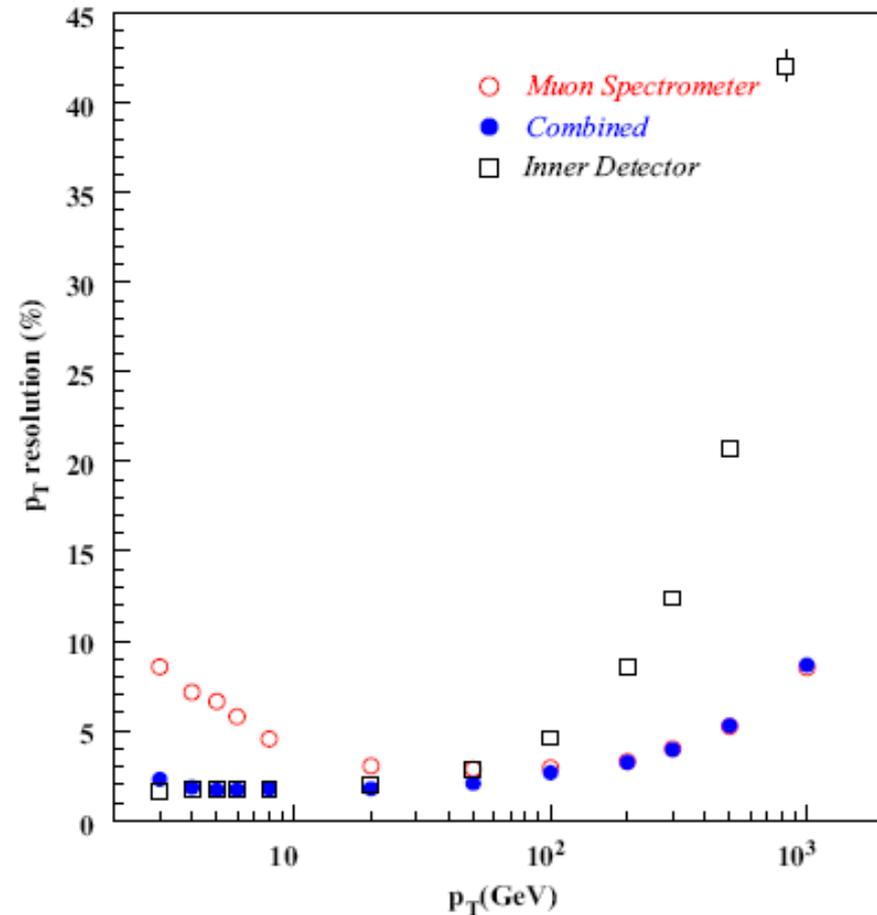


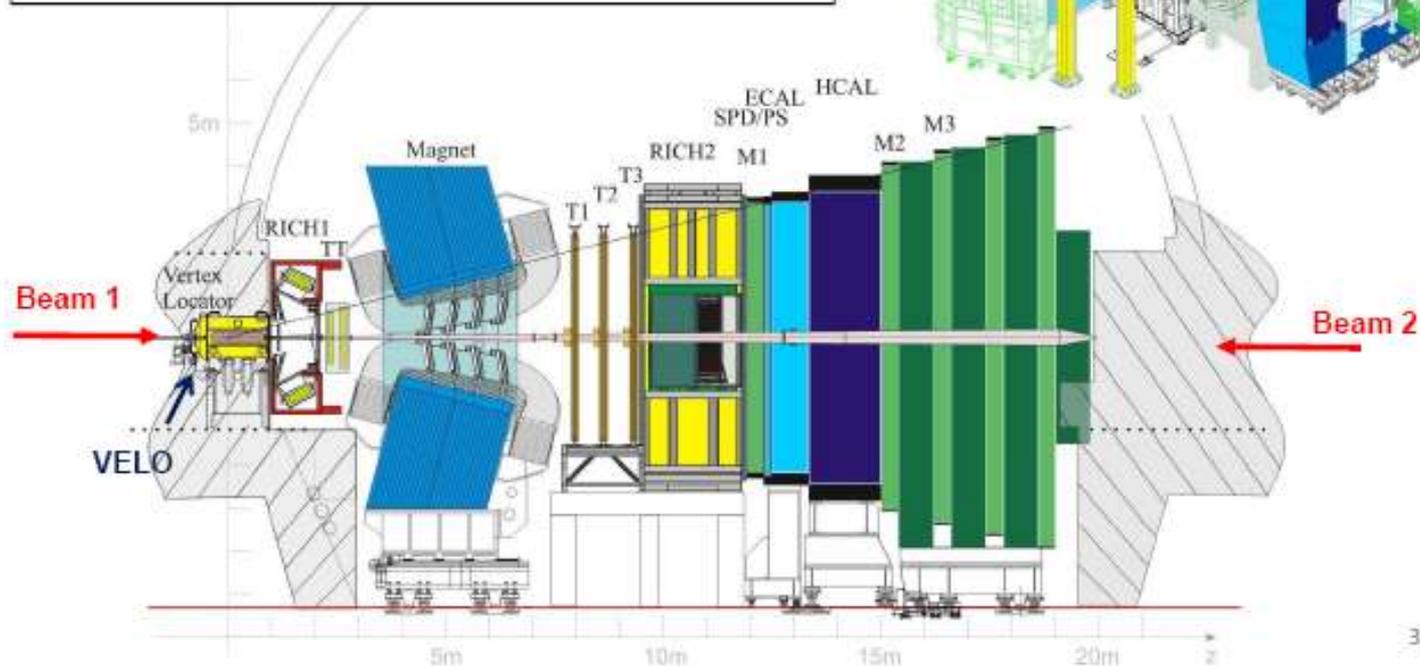
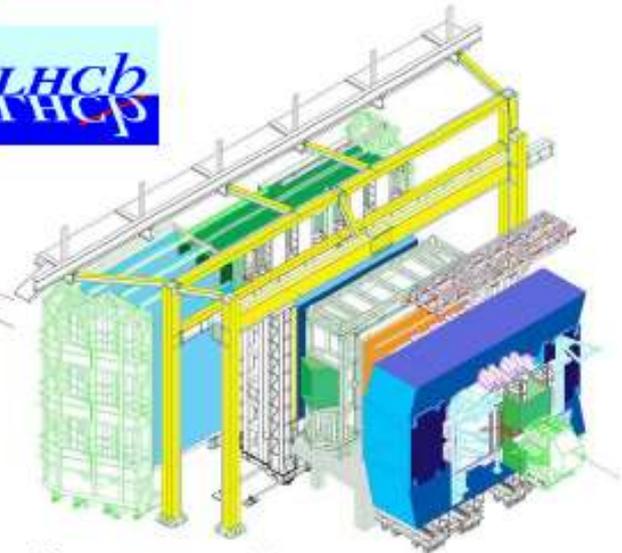
Fig. 1.  $p_T$  resolution of track reconstruction in the Muon System and in the Inner Detector, using the STACO procedure, as a function of  $p_T$ .

# Эксперимент LHCb – прецизионное измерение распадов B-мезонов

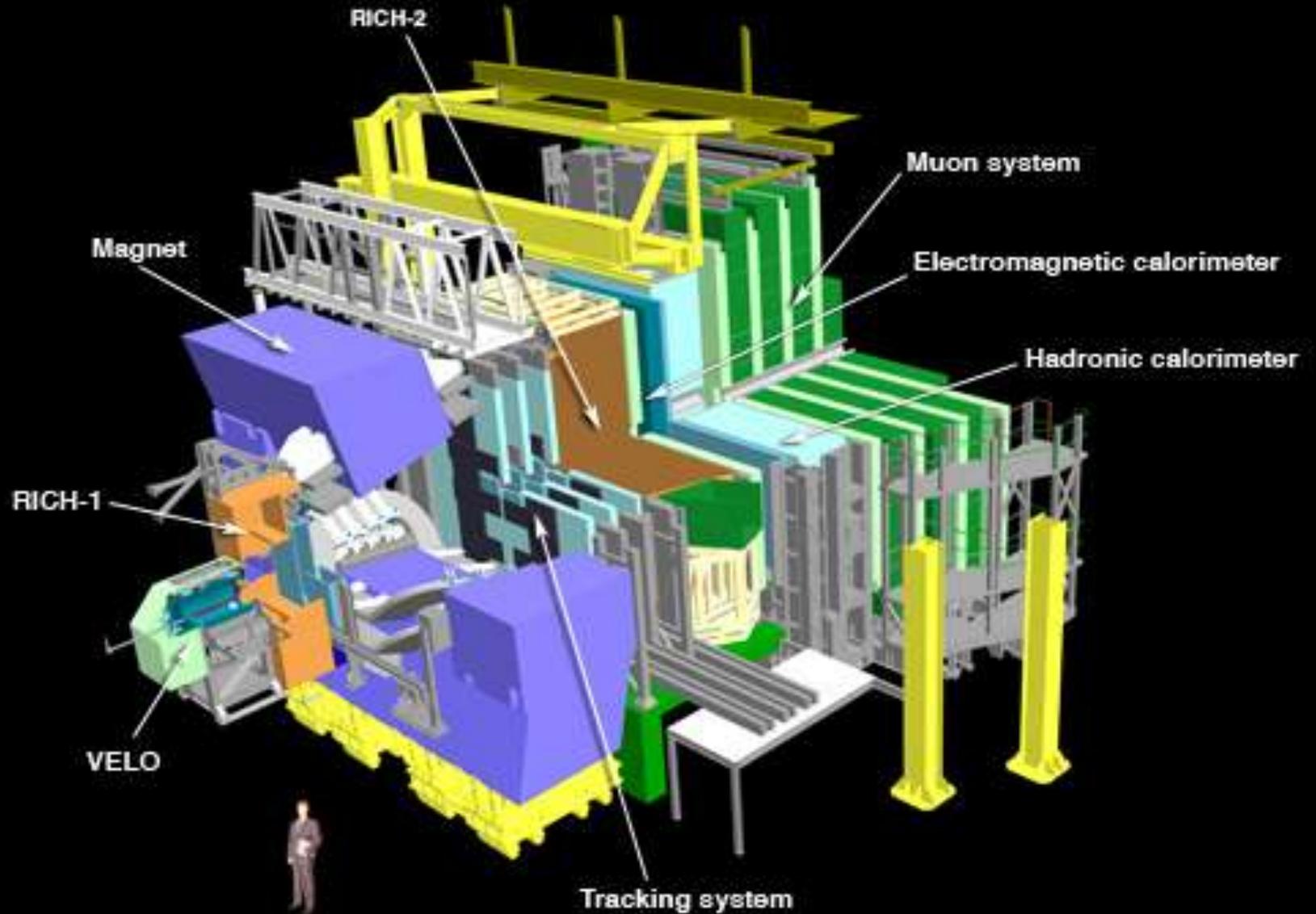
## LHCb: Study of B decays and CP Violation

- Dipole magnet (4 T.m)
- Particle Identification (2 RICH)
- 21 layer of Si microstrip detectors (VELO)
- Shashlik (Pb/scint) em calorimeter
- HCAL (Fe/scint),
- MWPC muon system

LHCb  
LHCb



# LHCb



# Разрешение по массе $B$ -мезона при измерении распада $B \rightarrow \mu\mu$ *LHCb – 20 МэВ; CMS – 40 МэВ; ATLAS – 80 МэВ*

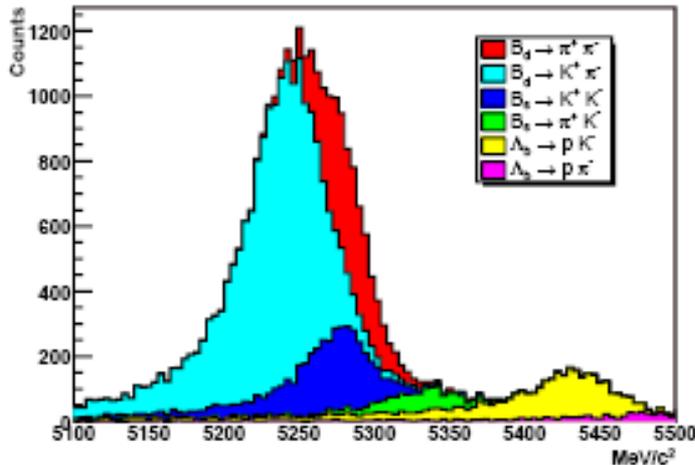
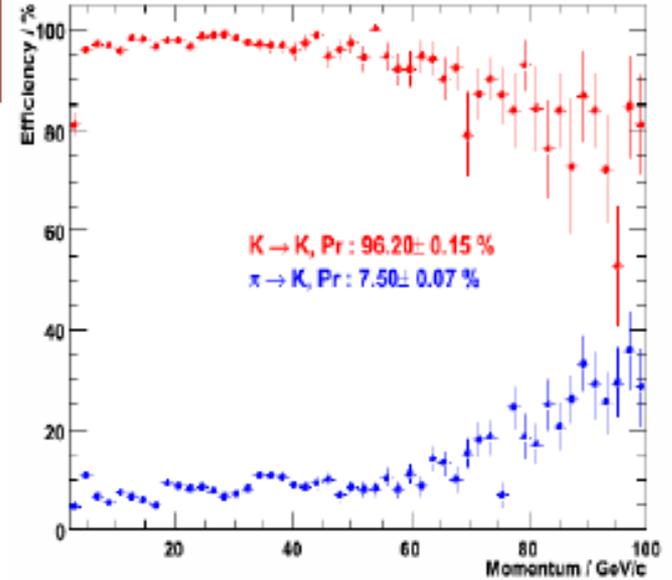
## LHCb RICH performance

Hadron ID from 1-100 GeV/c

3 radiators: Aerogel,  $C_4F_{10}$ ,  $CF_4$

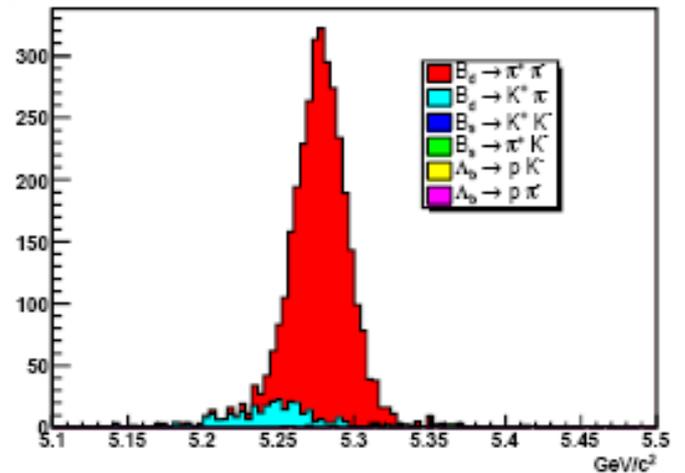
484 HPDs: 2.8m<sup>2</sup> with 2.5 x 2.5mm<sup>2</sup> pixels

Allows rare B-decay to be cleanly identified



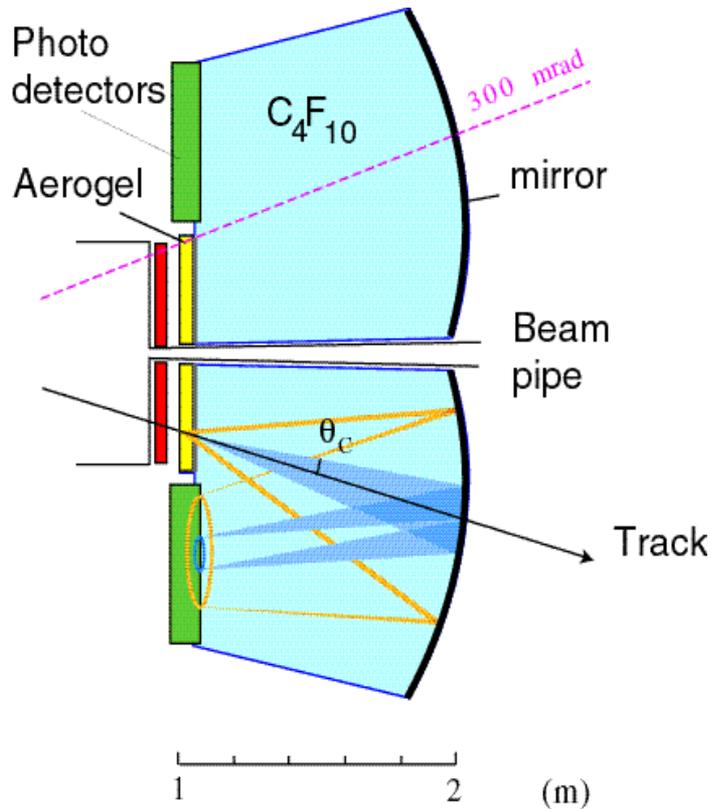
Without RICH

LHC



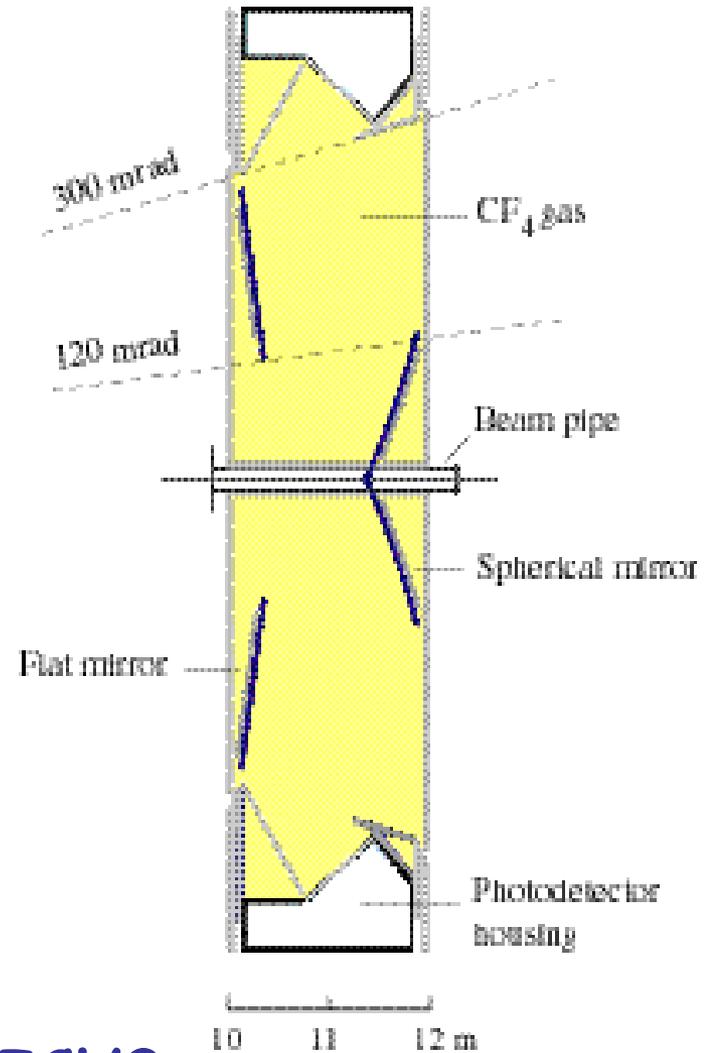
With RICH

# RICH system Overview



## RICH1:

5cm aerogel  $n = 1.03$ , 2-11 GeV  
 4 m<sup>3</sup>  $C_4F_{10}$   $n = 1.0014$ , 10-70 GeV



## RICH2:

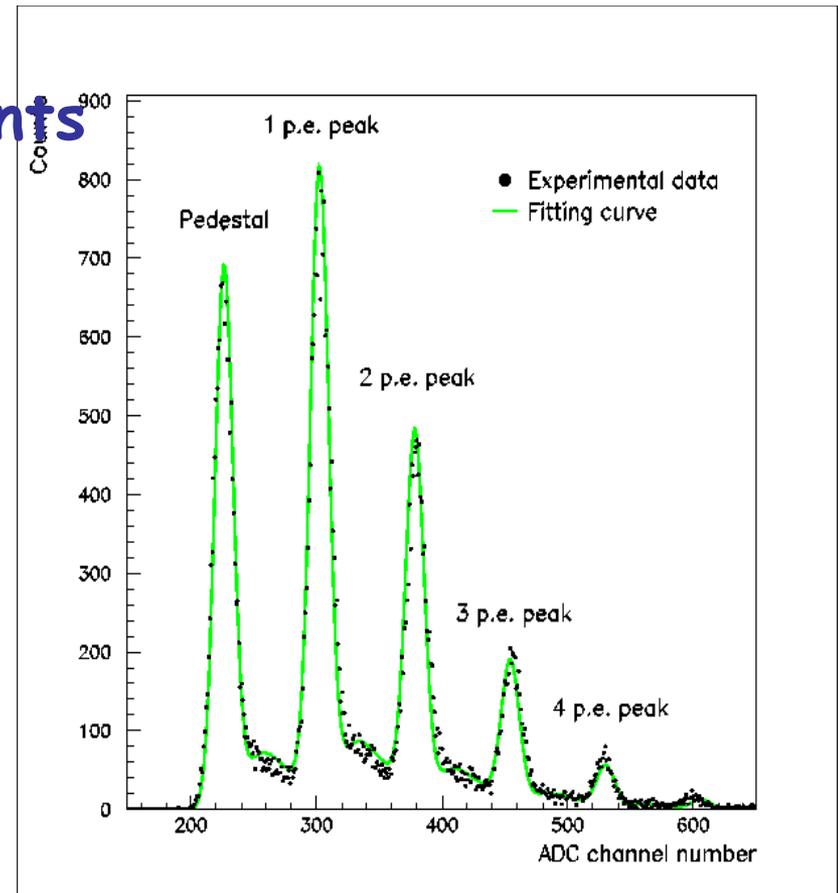
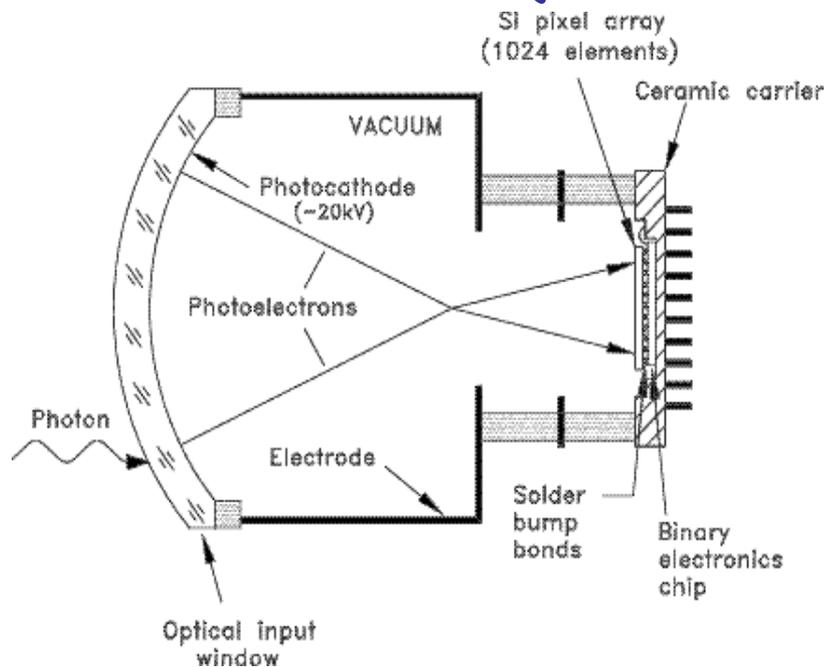
100 m<sup>3</sup>  $CF_4$   $n = 1.0005$ , 17-150 GeV

# RICH system Overview

## RICH photodetector requirements

- Cover total area  $\sim 2.6 \text{ m}^2$
- Single photon sensitivity
- Granularity  $\sim 2.5\text{mm} \times 2.5\text{mm}$
- Visible and UV sensitivity
- 25ns time resolution

## 80mm Pixel HPD (schematic)



Good photoelectron resolution  
Low occupancy



Binary Readout electronics

# Дрейфовые трубки внешнего трекера LHCb

264 модуля 5м x 0.34 м  
с 53 766 трубками

Внутренний диаметр трубки  
4.9 мм

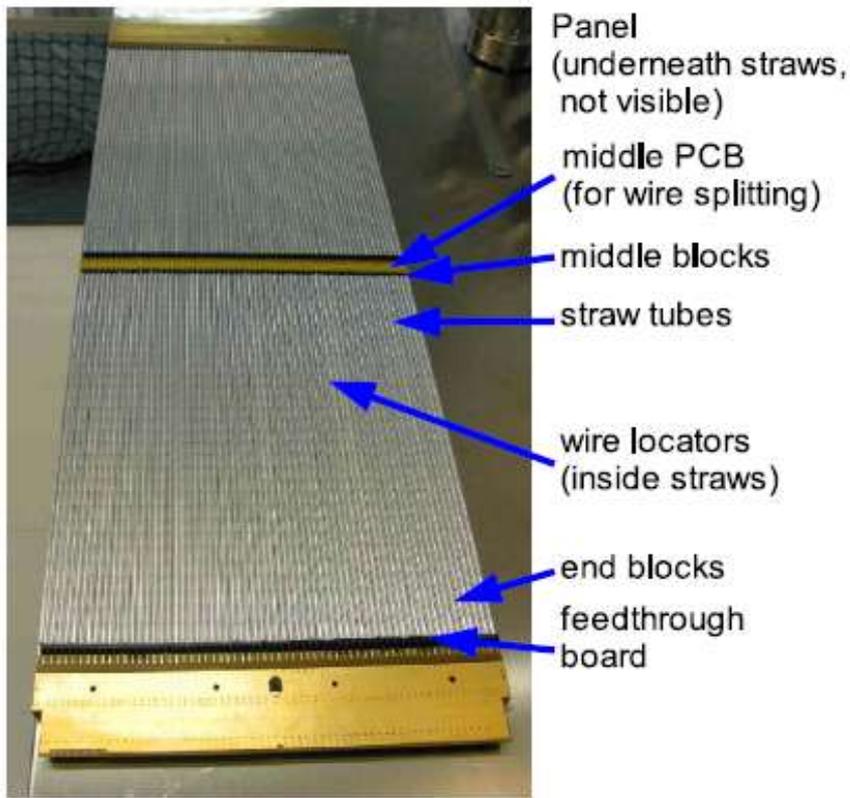
Полный размер детектора 5м  
x 6 м

Толщина детектора 0.7X0

Пространственное  
разрешение 200 мкм

Достижимо при точности  
позиционирования при  
склейке трубок 100 мкм

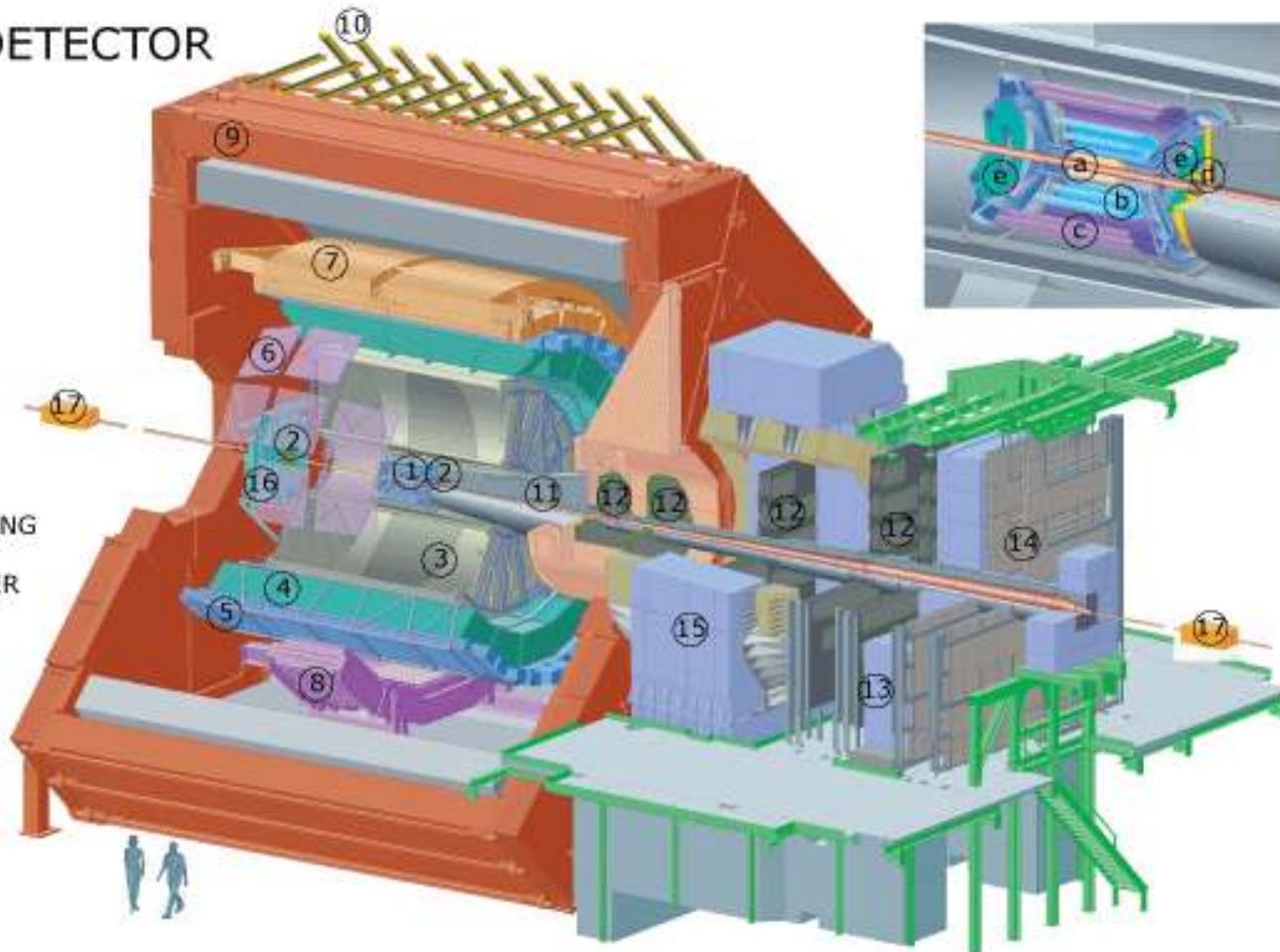
Обеспечит разрешение по  
импульсу 0.2 %



# Эксперимент ALICE

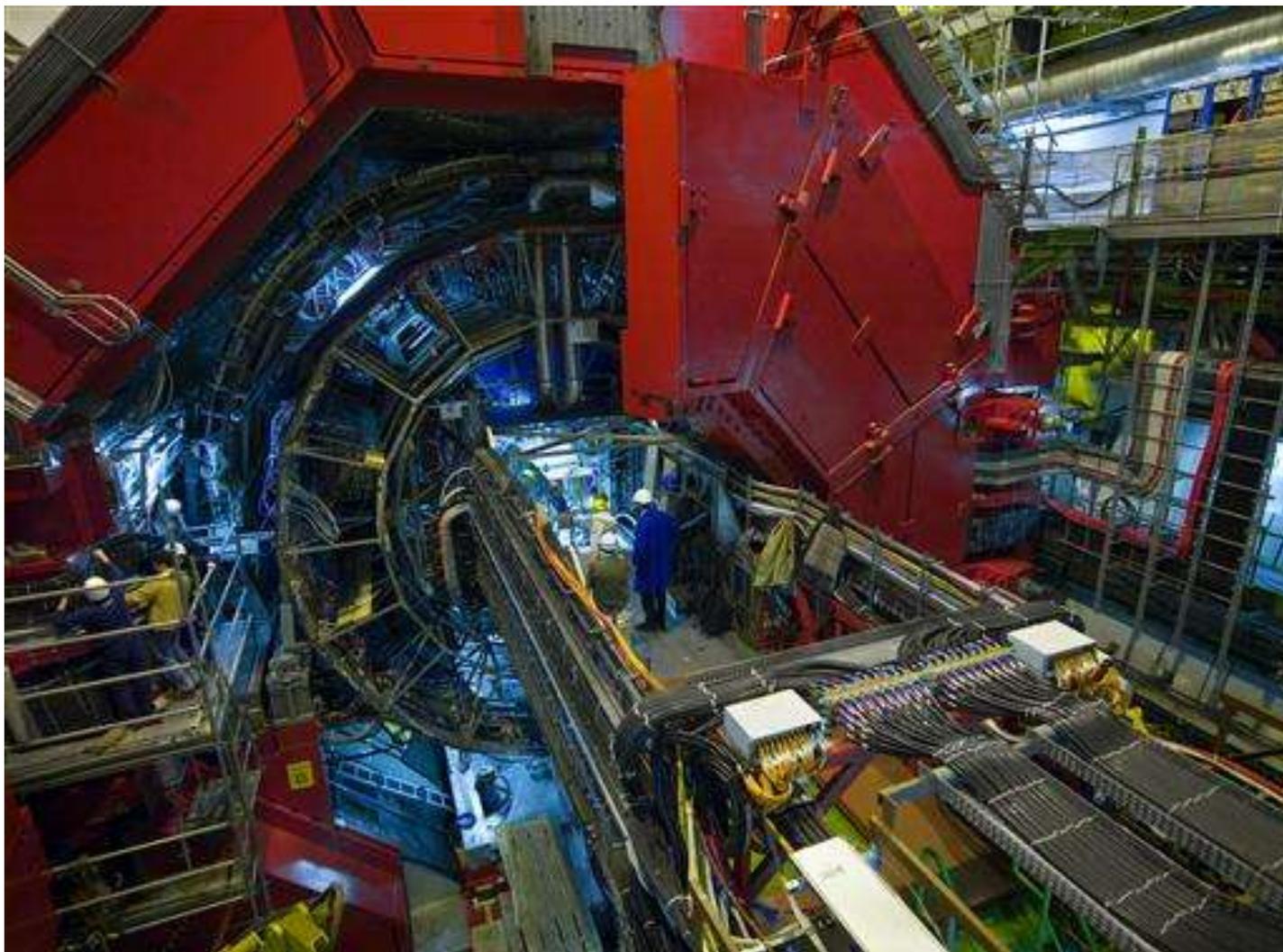
## THE ALICE DETECTOR

1. ITS
2. FMD , T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCAL
8. PHOS CPV
9. MAGNET
10. ACORDE
11. ABSORBER
12. MUON TRACKING
13. MUON WALL
14. MUON TRIGGER
15. DIPOLE
16. PMD
17. ZDC

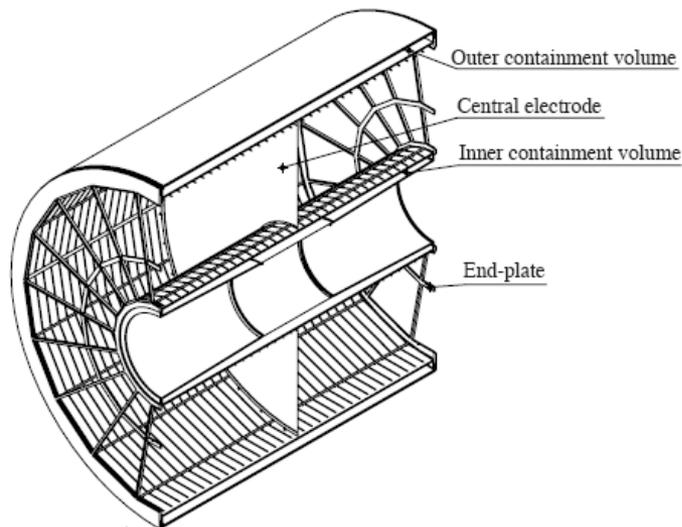


- a. ITS SPD Pixel
- b. ITS SDD Drift
- c. ITS SSD Strip
- d. V0 and T0
- e. FMD

# *ALICE в начале 2008г.*



# ALICE TPC



**Figure 28.13:** The ALICE TPC shown in a cutaway view. The drift volume is 5 m long with a 5 m diameter. Gas amplification is provided by planes of anode wires.

The TPC is cylindrical in shape with an active radial range from about 85 to 250 cm, and an overall length along the beam direction of 500 cm, divided by the central HV electrode into two drift regions of 250 cm length. Multi-wire proportional chambers are mounted into 18 trapezoidal sectors in each end-plate.



# ALICE

ALICE is the only experiment at the Large Hadron Collider dedicated to the investigation of heavy ion collisions. The ALICE Time-Projection Chamber (TPC) [1] is the main tracking detector in the ALICE central barrel, situated between a silicon vertex detector (ITS) [2] on the inside, a Transition-Radiation Detector and a Time-of-Flight array on the outside. It covers the pseudo-rapidity range  $|\eta| < 0.9$ .

The TPC has been designed for a maximum multiplicity  $dN_{\text{ch}}/dy = 8000$ , resulting in 20000 charged primary and secondary tracks in the acceptance, an unprecedented track density for a TPC. Although this multiplicity might be higher by a factor of 4 than the extrapolation from RHIC data, this upper limit has been kept for the design and

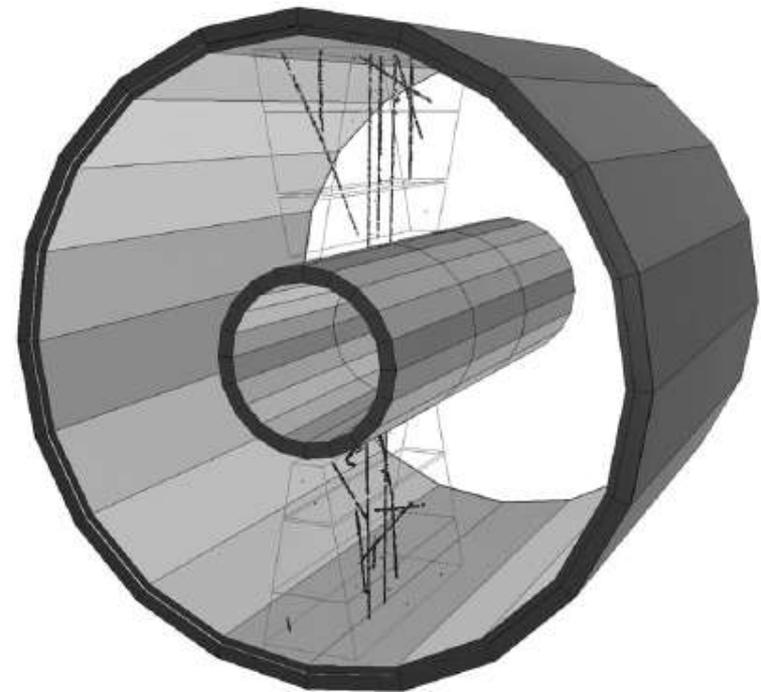
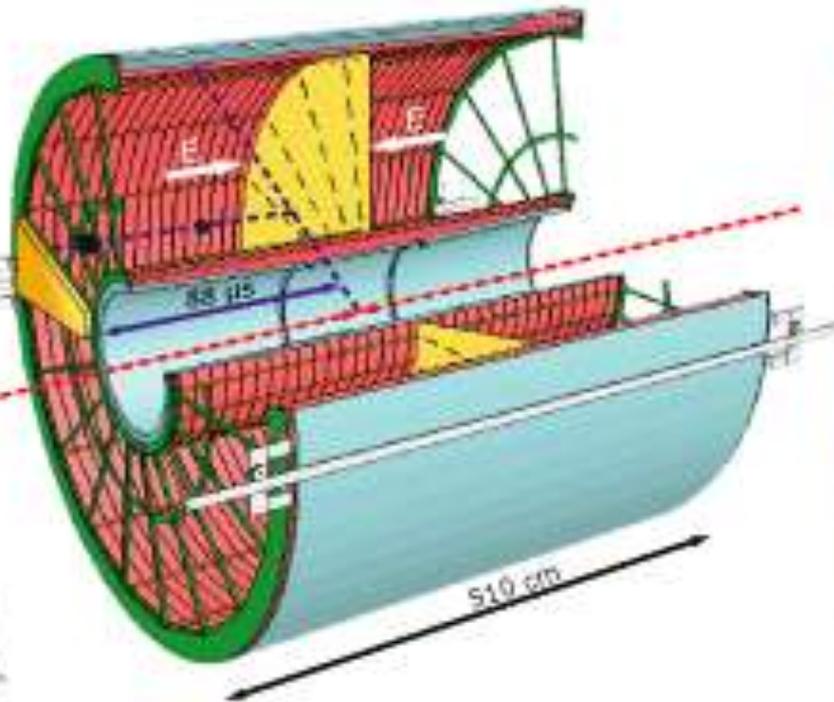


Fig. 1. Three-dimensional view of a cosmic ray event as seen in two TPC sectors.

# ALICE TPC



Readout Chambers



GAS VOLUME: 88 m<sup>3</sup>  
DRIFT GAS 90% Ne - 10% CO<sub>2</sub>



HV electrode (100 kV)



End Plate



Field Cage

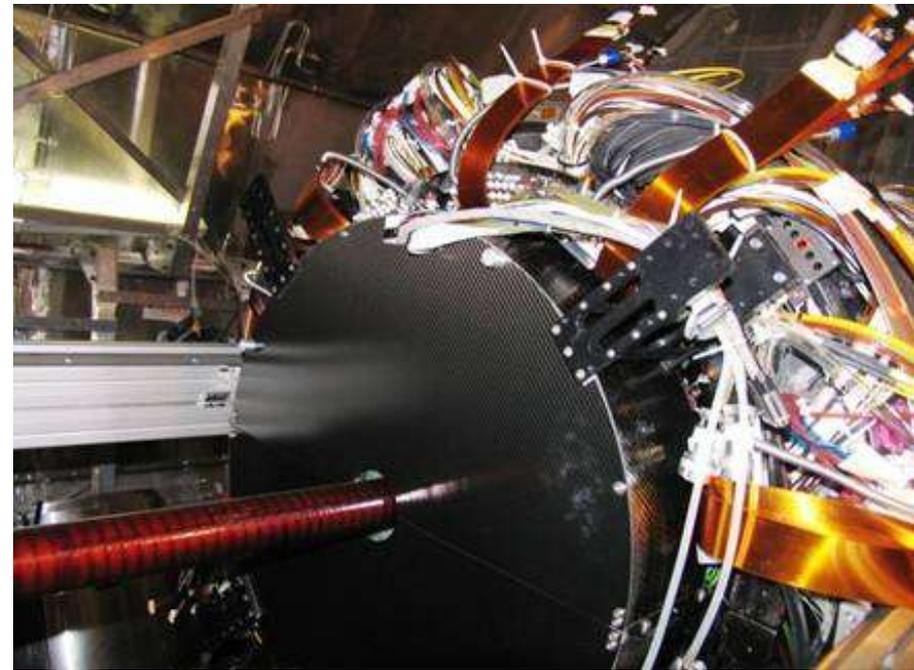
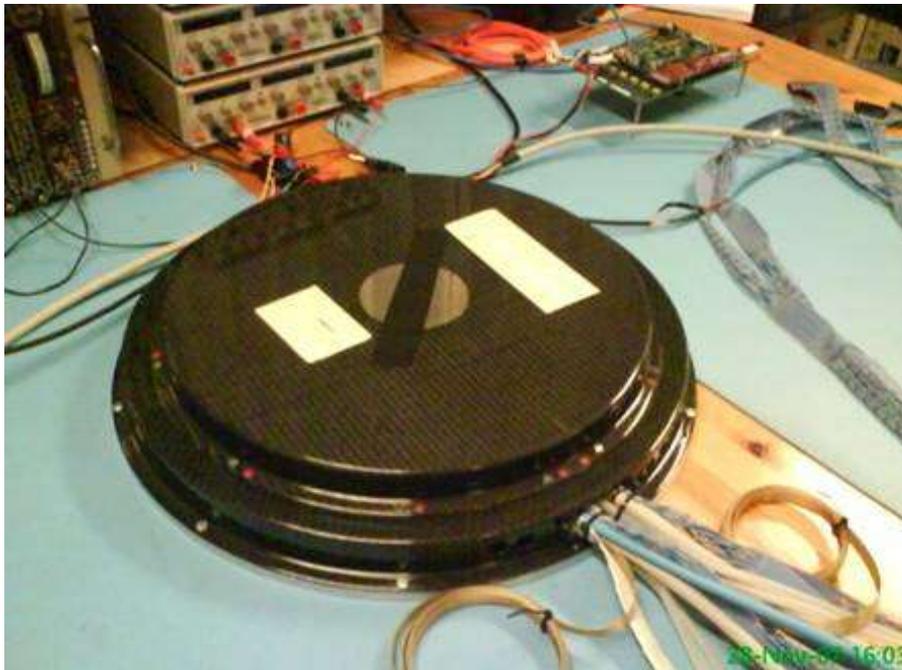
The position resolution of the TPC including all effects is expected to vary from 1100 to 800  $\mu\text{m}$  in  $\varphi$ -direction and 1250 to 1100  $\mu\text{m}$  in  $z$ -direction, depending on  $r$  and  $z$ . The  $dE/dx$  resolution in simulation for isolated tracks is 5.3%. Careful treatment of the amplitude splitting leads to an only moderately increased value of 6.5% at  $dN/dy = 8000$ .

Considerable effort has gone into the pattern recognition and tracking software, where now a track efficiency of about 97% (of geometrically accepted tracks) has been reached in simulation for the maximum multiplicity, a value we did not expect to be obtainable in the beginning. The momentum resolution for the TPC alone or combined with the other tracking devices, is shown in Fig. 1. For  $dN/dy = 6000$  and a magnetic field of 0.5 T, the expected combined resolution is better than 4% at 100 GeV/ $c$ , implying excellent performance also for hard probes. To

# Трековые детекторы ALICE

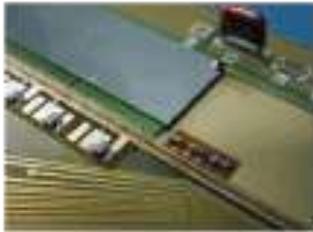
Передний детектор  
множественности FDM :  
5 колец двусторонних Si  
детекторов  
с 51 200 стрипами

Разработан и изготовлен в  
Копенгагене



# ALICE Pixel Detector

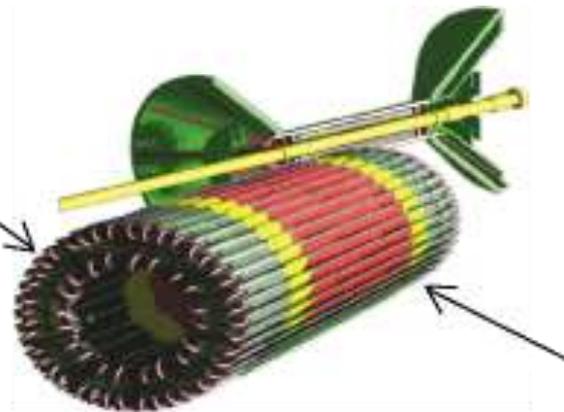
- SPD is to provide ALICE with adequate secondary vertexing capability for charm and beauty detection in such a high multiplicity environment (charged particle multiplicities of up to 8000 per unit of rapidity have been predicted for head-on Pb-Pb collisions at the LHC). The pseudorapidity coverage of the inner layer is  $|\eta| < 1.95$ . The two SPD layers allow to achieve a track impact parameter resolution in the plane perpendicular to the beam axis better than  $50 \mu\text{m}$  for  $p_t > 1.3 \text{ GeV}/c$ .



Photograph of a ladder mounted on a prototype bus



Design of the carbon fiber support of one sector



Schematic drawing of the two barrel layers



Pixel bus with 10 chips (half-stave configuration)

# Заключение

- *Детекторы LHC воплотили самые передовые технологии, развитые в последние 10-15 лет.*
- *Российский вклад в создание детекторов значителен.*
- *Россия располагает многими технологиями, используемыми при создании детекторов*
- *Ведутся разработки для SLHC, ILC, FAIR, sBfactories, Biomed*